LUISS

Department of Law

Chair of Green and Sustainable Finance

“TRANSITION IN THE SHIPPING SECTOR: BANK’S ASSESSMENT OF ALTERNATIVE FUELS AND CLIMATE AND ENERGY SOLUTIONS”

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Academic Year 2024/2025

Abstract

The ecological transition of the maritime sector represents one of the most complex and strategic challenges for the global economic and financial system. Despite the adoption of ESG criteria by financial institutions, the models currently used to assess risk and guide financing instruments in the shipping sector are still too generic, neglecting the profound operational, technological, and economic differences between vessel types. This thesis proposes an innovative framework that enables banks to integrate vessel type-specific sustainability indicators (KPIs) into decision-making processes to improve the accuracy of risk assessments, optimize resource allocation, and effectively incentivize decarbonization of the industry. The analysis combines a critical review of existing literature, a detailed assessment of key sustainable finance instruments, and an advanced exploration of emerging technologies, while also integrating the role of international and European regulations. The goal is to offer an operational model for ESG analysts and financial institutions to guide the shipping energy transition with a granular, technical and climate-aligned approach.

Keywords: Sustainable finance, Maritime decarbonization, ESG risk, Climate-aligned credit, KPI integration, Ship classification, Environmental metrics, Transition risk, Green shipping, Banking allocation model, Poseidon Principles, EU Taxonomy, Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), Sustainability-linked finance, Vessel segmentation, Shipping sector regulation, Upstream emissions, Alternative fuels compatibility, Financial risk assessment.

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Introduction

The maritime sector, responsible for transporting over 90% of global goods[1], is simultaneously a cornerstone of economic globalization and a significant source of greenhouse gas emissions, accounting for approximately 3% of the global total. Within a regulatory and financial landscape that is increasingly aligned with the objectives of the Paris Agreement and the European Green Deal, the industry is now compelled to undertake a profound technological and environmental transition. At the heart of this process lies the financial system, and particularly the banking sector, which is playing an increasingly strategic role in financing low-emission solutions and integrating Environmental, Social, and Governance (ESG) criteria into decision-making models.

Nevertheless, the current methodologies used to assess credit risk and structure financial instruments in the shipping sector remain largely standardized, failing to capture the technological, operational, and environmental heterogeneity across vessel types. This lack of granularity undermines banks' ability to allocate capital efficiently, identify transition risks accurately, and credibly contribute to the decarbonization of maritime transport.

This dissertation aims to address these limitations by developing an analytical and operational model that integrates vessel-specific environmental Key Performance Indicators (KPIs) into financial processes to support a climate-aligned and technically calibrated transition.

The work is structured into five chapters, each following a coherent methodological and conceptual progression. The first chapter provides a critical review of the existing literature and the underlying theoretical framework, exploring key academic and institutional contributions related to maritime sustainability and responsible finance. It also introduces the concepts of climate risk, environmental materiality, and the systemic role of banks in the energy transition.

The second chapter focuses on the role of banks and climate risk assessment tools supporting the maritime transition. Regulatory instruments such as the EU Taxonomy, the Corporate Sustainability Reporting Directive (CSRD), and the Poseidon Principles are examined, along with the latest guidelines issued by the European Banking Authority (EBA) concerning ESG risk integration in credit processes.

The third chapter introduces a technical classification of major commercial vessel types including bulk carriers, tankers, container ships, LNG carriers, general cargo ships, and ro-ro vessels analyzing their structural, propulsion, and operational features relevant to the assessment of their

[1] Stopford, M. (2009). *Maritime Economics* (3rd ed.). Routledge.

decarbonization potential. Special attention is paid to the technological constraints and innovation capabilities specific to each class.

The fourth chapter investigates environmental metrics and KPIs applicable to the maritime sector. These include the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), the Carbon Intensity Indicator (CII), indicators of compatibility with alternative fuels, and assessments of upstream emissions embedded in shipbuilding materials. Each KPI is evaluated in terms of robustness, comparability, verifiability, and relevance for integration into ESG risk scoring and financial decision-making models.

Finally, the fifth chapter develops a technical-operational framework for the integration of KPIs into banking processes. It proposes a differentiated financial allocation model based on vessel typology, linking each vessel's environmental and technological profile to specific sustainable finance instruments such as green loans/bonds, sustainability-linked instruments, and transition bonds and loans. The framework outlines a credit strategy that incorporates transition risk, shipowner resilience, and alignment with institutional climate goals.

Overall, the thesis seeks to provide a methodological and practical contribution to the development of a truly sustainable maritime finance model that combines technical precision, environmental responsibility, and financial soundness.

Research Question

Currently, the financial instruments adopted by banks to support the decarbonization of the maritime sector are often based on generic decarbonisation indicators at fleet level that do not reflect the operational, technical and economic differences between different types of ships. This approach does not consider the complexity of the sector, leading to inaccurate risk assessments and inefficient allocation of financial resources. The main gap that needs to be filled is the lack of a more granular framework to integrate sustainability KPIs specific to each ship category into financial risk assessment and financing decisions.

With the following research question, "**How can banks integrate ship-type-specific sustainability KPIs in assessing financial risk and allocating the most appropriate financing instruments to incentivize the maritime sector's transition to decarbonization?**" my study aims to overcome these limitations through a detailed analysis that examines the sector on a ship-by-ship basis, identifying targeted sustainability KPIs for each ship type.

This more detailed structure will allow me to define a more precise and calibrated financial strategy, linking each type of ship to the most appropriate financing instruments, with the goal of identifying the most effective financial mechanisms to incentivize transition without compromising the economic stability of shipowners and financial institutions.

The decision to finance the construction and operation of vessels and fleets should be based on a thorough analysis of its environmental efficiency, its prospects for adapting to future regulations, and its impact on the financial institution's sustainability and decarbonization strategy. However, current models for assessing financial risk in the shipping industry are not sufficiently granular to distinguish between different types of ships and their specific technological and operational requirements. Through this research, I intend to provide an innovative framework aimed at moving beyond the current models, offering a smarter, more calibrated approach to transition finance and enabling banks to optimize the financing of the energy transition in the shipping sector, ensuring more effective use of financial resources and maximizing the impact of decarbonization. Such a framework will not only make financing strategies more targeted and optimized but will also help strengthen the role of the financial sector as a catalyst for the energy transition in shipping, accelerating the adoption of sustainable and innovative solutions.

Chapter 1. Literature Review & Theoretical Framework.

1.1. The Multiplier Effect of Shipping Emissions

Beyond its direct environmental footprint[2], the shipping sector exerts a powerful multiplier effect on global emissions. Maritime transport is the backbone of international trade, facilitating the movement of over 80% of globally traded goods by volume and over 70% by value[3]. This pivotal role means that shipping not only emits directly through the combustion of fossil fuels but also indirectly amplifies the carbon footprint of global supply chains. Port operations, container handling, inland logistics, warehousing, and last-mile delivery all depend on maritime transport and cumulatively generate substantial additional emissions. For example, recent studies have shown that emissions from port activities alone—including cargo handling equipment and terminal operations—can account for up to 18% of a port's total carbon footprint[4]. Furthermore, the availability of efficient, low-cost shipping routes encourages geographically dispersed production and consumption networks, leading to intensified resource extraction, increased energy use in manufacturing, and a higher demand for long-haul logistics—all of which raise global GHG emissions.

Notably, globalization trends such as just-in-time production and the fragmentation of global value chains—enabled precisely by the efficiency of maritime shipping—have contributed to a nearly 70% increase in trade-related emissions between 1995 and 2015[5], highlighting how shipping acts as a silent multiplier of global environmental impact.

In this perspective, decarbonizing the shipping sector is not merely a technical priority but a strategic step toward reshaping global production and consumption models, making them compatible with the goal of a fair and lasting ecological transition.

The shipping business is a cornerstone of the global economy, accountable for the transportation of over 90% of internationally traded goods[6]. With a fleet of over 100,000 merchant vessels traversing the oceans, it links continents and facilitates global logistical networks. Considering the climate issue, the marine industry has a significant challenge: the IMO aims to reduce carbon intensity by 40% by 2030 and attain net zero emissions by 2050. To achieve these goals, large-scale adoption of low-emission alternative fuels will be crucial.

During the 83rd session of the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO), held in London from 7 to 11 April 2025, significant

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[2] International Maritime Organization. (2020). *Fourth IMO GHG Study 2020*. IMO.
[3] United Nations Conference on Trade and Development. (2023). *Review of Maritime Transport 2023*. UNCTAD
[4] International Council on Clean Transportation. (2022). *The climate impact of port activities: A global assessment*. ICCT
[5] Organisation for Economic Co-operation and Development. (2020). *Globalisation and Trade-Related Emissions*. OECD
[6] International Maritime Organization (2022). "Fourth IMO GHG Study"

progress was made toward establishing a new regulatory framework aimed at steering the maritime sector toward climate neutrality. Central to the discussions was the preliminary approval of the "IMO Net-Zero Framework,"[7] a comprehensive and legally binding package of measures designed to achieve net-zero greenhouse gas (GHG) emissions from international shipping by 2050, aligning with global efforts to limit climate change.

The framework is structured around two main pillars: first, the introduction of a technical standard to progressively reduce the carbon intensity of marine fuels; and second, the implementation of a global economic mechanism for GHG pricing, aiming to internalize the environmental costs associated with fossil fuel consumption. These measures, which will be formally adopted during an extraordinary session scheduled for October 2025, will apply to ships over 5,000 gross tonnages—responsible for approximately 85% of total CO_2 emissions from the sector—and are set to enter into force starting in 2027.

In parallel with the climate-focused measures, the MEPC 83 session addressed several other critical marine environmental issues. Among these were the adoption of an updated action plan to tackle marine plastic litter, revisions to the NOx Technical Code to further regulate nitrogen oxide emissions, and the designation of new Emission Control Areas (ECAs) and Particularly Sensitive Sea Areas (PSSAs), which will receive enhanced environmental protection due to their ecological vulnerability.

In summary, the 83rd MEPC session marked a historic advancement in environmental governance for international shipping, laying the groundwork for a global transition toward more sustainable operational models and making a substantial contribution to international climate mitigation efforts.

The environmental impact of shipping is considerable: the sector currently accounts for around 3% of worldwide CO_2 emissions[8], positioning it as a principal source of greenhouse gases (GHGs). This is particularly relevant in a context where environmental sustainability and energy transition are central to international policies. Ship emissions and discharges contribute to air and marine pollution, directly affecting human health and ecosystems, necessitating regulatory measures and technological advancements to alleviate the sector's impact. The EMSA report of February 4, 2025[9], shows progress in maritime transport toward sustainability, although emphasizes the necessity to expedite initiatives aimed at attaining carbon neutrality by 2050. *"CO_2 emissions from the European maritime industry have risen since 2015, with the exception of 2020, reaching 137.5 million tons, while an increase of 8.5% in 2022 from the prior year[10], still being below pre-pandemic levels"* (Chart1).

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[7] https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-83rd-session.aspx
[8] European Commission (2023). "Fit for 55: The Inclusion of Shipping in the EU ETS".
[9] European Environment Agency & European Maritime Safety Agency. (2025). European Maritime Transport Environmental Report.
[10] Source: EEA, 2022c.

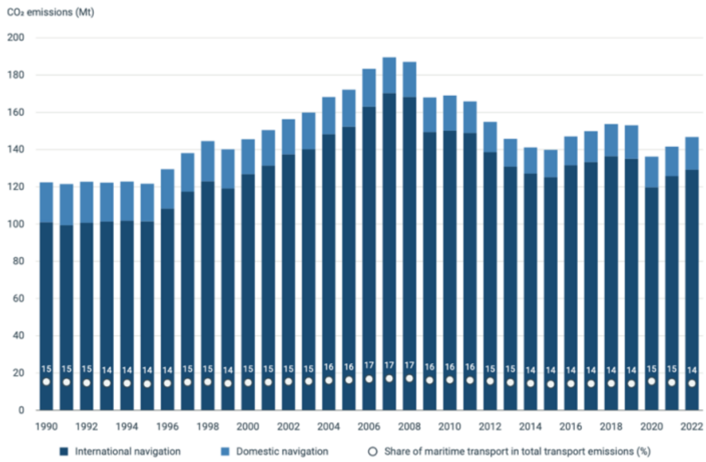

Chart 1. CO2 emissions from the maritime sector and their share in total transport emissions between 1990 and 2022 in the EU-27

“Methane emissions (CH_4) more than doubled between 2018 and 2023, accounting for 26% of transport methane emissions in 2022[11]*, due to the increasing adoption of LNG”* (Chart 2).

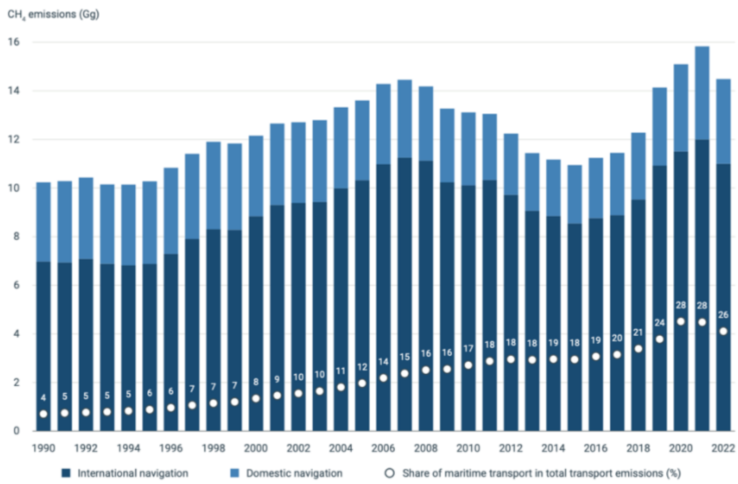

Chart 2. CH4 emissions from the maritime sector and their share in total transport emissions (%) in the EU-27

“The establishment of Emission Control Areas (SECAs) has resulted in a 70% decrease in sulfur oxides (SOx) emissions since 2014[12] (Chart 3), *however nitrogen oxides (NOx) emissions have risen by 10% from 2015 to 2023”* (Chart 4).

[11] Source: UNFCCC (EEA, 2022).
[12] Source: LRTAP (EEA, 2024).

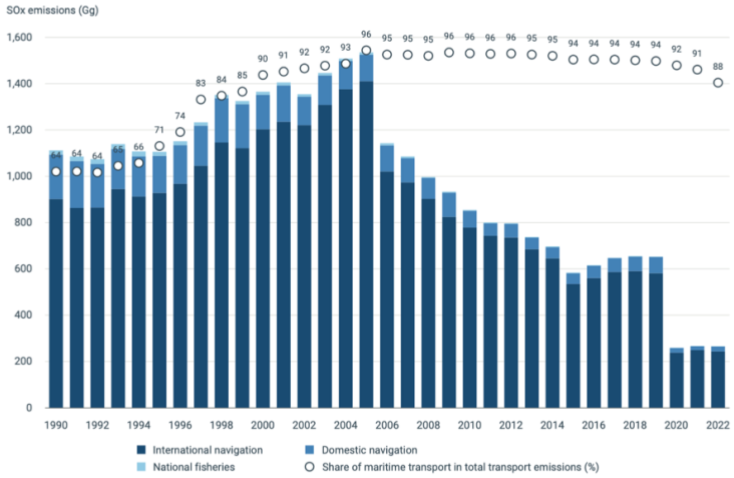

Chart 3. SOx emissions from the maritime sector and their share in total transport emissions in the EU-27

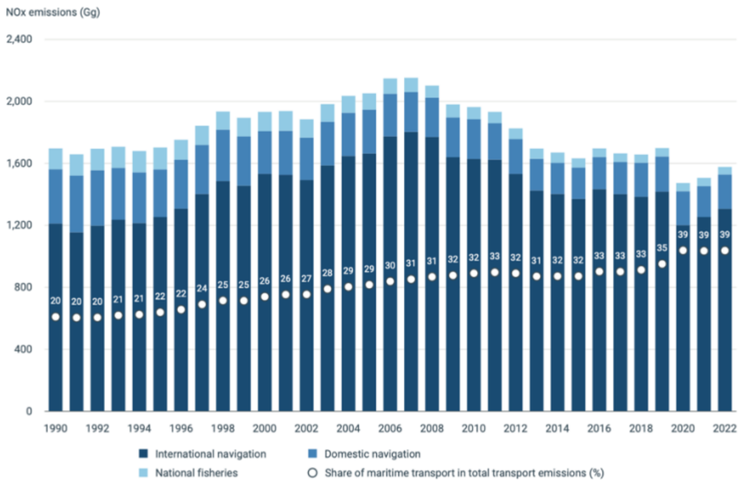

Chart 4. NOx emissions from the maritime sector and their share in total transport emissions in the EU-27

The report also highlights the environmental impacts of shipping, including a 40% increase in graywater releases from 2014 to 2023 and damage to Europe's coastal seabed (27% of the seabed disturbed, with 5% severely damaged). Furthermore, maritime traffic has increased the risk of collision with marine wildlife in Natura 2000[13] protected areas from 2017 to 2022.

The path towards a sustainable maritime industry is intricate, encompassing numerous technical, economic, and regulatory obstacles. However, with collaboration among businesses, institutions, and investors, the sector can accelerate the transition to a low-emission model, significantly contributing to global efforts to combat climate change and protect the marine ecosystem. Ricardo's "A Zero Emission Blueprint for Shipping"[14] report emphasizes the imperative of investing in research and development to advance these emerging technologies. It delineates 265 essential initiatives aimed at

[13] "Natura 2000 is a network of sites of Community interest (SCI) and special protection areas (SPAs) created by the European Union for the protection and conservation of habitats and species, animals and plants, identified as priorities by the Member States of the European Union".
[14] Ricardo. (2021). *A zero emission blueprint for shipping*. International Chamber of Shipping.

tackling technological and infrastructural challenges, emphasizing the necessity for collaborative engagement among industry stakeholders, governmental bodies, and financial institutions to obtain the $5 billion required for the pre-commercial implementation phase.

The subsequent sections will thoroughly examine the principal international and European regulations governing sustainable maritime transport, emerging technological solutions for decarbonization—including novel fuel types, innovative materials, and propulsion systems—and the role of banking institutions and financial instruments in facilitating this transition, referencing the existing literature on the topic.

1.2. Drivers of Change

Successfully navigating the transition and decarbonization of the shipping sector requires a proactive understanding of the key drivers shaping its evolution. For shipping companies and the financial institutions that support them, the ability to effectively manage emerging risks and leverage new opportunities will be fundamental to ensuring long-term competitiveness. A clear identification of these drivers is essential for comprehending both the challenges and the prospects associated with the sector's transformation.

Among the key forces driving this transformation are the definition of global decarbonization targets and the tightening of regulatory frameworks; innovations in vessel design and fuel efficiency; the adoption of alternative fuels; the adaptation of maritime infrastructure; and the growing emphasis on supply chain resilience. Additional drivers include changes in consumer behaviour linked to e-commerce expansion, the spread of automation and digitalization, and economic shifts affecting trade volumes. Social and governance factors, such as crew welfare improvements, investor activism, and stricter labor standards, are becoming increasingly relevant. Environmental concerns are also critical, with initiatives focused on waste management, ballast water control, biofouling management, and the impact of climate change on maritime routes. Moreover, partnerships with the energy sector, access to green financing, the influence of NGOs, and technological advances in ports and logistics are shaping the future of the industry. Finally, the cyclical nature of shipping markets continues to affect strategic planning and investment decisions.

1.2.1 Global Decarbonization Targets and Regulatory Frameworks

The global shipping sector, recognized as a major contributor to international greenhouse gas (GHG) emissions, is increasingly subjected to a complex and evolving set of decarbonization targets and regulatory measures. According to the International Energy Agency (IEA)[15], maritime transport accounts for approximately 3% of global CO_2 emissions—a share comparable to that of some of the world's largest emitting nations[16].

In response to the urgent need for emissions reductions, international frameworks, particularly those established by the International Maritime Organization (IMO)[17], have set ambitious goals: notably, a commitment to reduce shipping-related GHG emissions by 50% by 2050 compared to 2008 levels. This overarching objective is supported by a range of technical and operational measures, including the Energy Efficiency Design Index (EEDI)[18] for newbuild vessels, the Energy Efficiency Existing Ship Index (EEXI) for the existing fleet, and the Carbon Intensity Indicator (CII)[19], which requires ongoing measurement and reporting of ships' carbon intensity performance.

Achieving compliance with these standards necessitates profound transformations in fleet operations, fuel usage, and ship management practices. To meet new requirements, shipping companies are increasingly investing in more energy-efficient vessel designs and exploring the use of alternative, lower-emission fuels such as liquefied natural gas (LNG), biofuels, methanol, and, prospectively, hydrogen and ammonia. Additionally, projects aimed at the partial electrification of vessels and the integration of renewable energy sources like wind and solar power are advancing, particularly for specific vessel types and operating routes.

The regulatory momentum extends beyond vessels to encompass port infrastructure. Ports are being encouraged to facilitate the transition by offering bunkering services for alternative fuels and providing shore-side electricity connections for berthed ships, thereby reducing emissions from idling engines. These initiatives are key components of broader efforts to establish "green corridors"—dedicated maritime routes designed to minimize emissions through coordinated actions among ports, shipping lines, fuel suppliers, and governments.

To support the financial demands of this transition, mechanisms such as green bonds and other sustainability-linked incentives are playing an increasingly important role. These instruments aim to mitigate the high upfront investment costs associated with adopting green technologies by linking financial advantages to environmental performance improvements.

Market dynamics are also a significant driver of change. Cargo owners, charterers, and financial institutions are applying pressure for more sustainable maritime practices, aligning their logistics

[15] International Energy Agency. (2023). *International shipping*.
[16] https://www.iea.org/energy-system/transport/international-shipping
[17] International Maritime Organization. (2023). *Revised GHG reduction strategy for global shipping adopted*
[18] DNV. *Energy Efficient Design Index regulations*.
[19] International Maritime Organization. (n.d.). *EEXI and CII - ship carbon intensity and rating system*.

requirements with their own decarbonization strategies. This demand-side push is accelerating the adoption of clean technologies across the industry.

Nonetheless, challenges remain in ensuring the consistent and equitable application of these targets across the global fleet. Significant disparities exist, particularly between developed and developing countries, where differences in technological readiness, financial capacity, and regulatory frameworks may hinder the pace of transition. Addressing these challenges requires substantial efforts in technology transfer, capacity building, and financial support mechanisms tailored to different regional contexts.

In conclusion, aligning the shipping sector with global decarbonization objectives is a multifaceted and demanding endeavour. It calls for integrated action across policy, technology, infrastructure, and finance, requiring collaboration among all stakeholders to secure a sustainable and economically viable future for international maritime transport.

1.2.2. Innovations in Vessel Design and Fuel Efficiency

Advancements in vessel design and improvements in fuel efficiency represent fundamental pillars of the shipping sector's strategy to address environmental challenges and meet evolving sustainability objectives. Recognizing the critical role of these innovations, the European Commission has taken a leading position in promoting research initiatives aimed at fostering the development of smarter, lighter, and more energy-efficient ships[20].

A key focus area has been the adoption of advanced materials, such as high-strength steel and composites, to build lighter vessels. Reducing a ship's weight directly decreases energy requirements for propulsion, leading to lower fuel consumption, decreased greenhouse gas emissions, and significant operational cost savings. In addition, these new materials enhance the durability and longevity of vessels, simultaneously reducing maintenance needs and life-cycle costs.

Ship design itself has also evolved to maximize hydrodynamic efficiency. Innovations such as optimized hull forms, which minimize drag, and specialized coatings that inhibit biofouling, contribute further to reducing fuel consumption. Improved flow dynamics allow vessels to navigate with less resistance, achieving better performance and lower emissions per voyage.

In terms of propulsion, hybrid technologies combining conventional engines with battery systems are gaining traction, especially for operations requiring variable speeds or manoeuvring in ports.

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[20] https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/lighter-fuel-efficient-ships-sustainable-future

Complementary technologies, such as air lubrication systems—which generate a layer of air bubbles between the hull and the water to minimize friction—offer additional gains in energy savings.
Another promising field involves energy recovery systems that capture waste heat from engine exhausts for reuse in onboard processes, improving overall energy efficiency and supporting auxiliary power generation.
Digitalization also plays a crucial role in boosting fuel efficiency. Sophisticated navigation tools, predictive route optimization software, and real-time monitoring systems based on sensors and data analytics allow for dynamic management of voyages, ensuring the most energy-efficient operational profiles under varying environmental conditions.
Furthermore, the ongoing transition toward alternative energy sources—such as liquefied natural gas (LNG), hydrogen, and ammonia—is reshaping vessel design requirements[21]. The integration of new fuel storage systems and adapted propulsion technologies is becoming a key factor in newbuild and retrofit strategies. It remains essential that these innovations align with stringent safety and performance standards. As a result, new technologies are typically developed in close collaboration with regulatory authorities to ensure full compliance and secure deployment.
In conclusion, the shipping sector's efforts to improve fuel efficiency and sustainability are being propelled by a diverse array of innovations in vessel construction, propulsion systems, and digital operations. These advancements are not only critical for minimizing the environmental impact of maritime transport but also indispensable for securing the industry's economic viability in a future increasingly shaped by sustainability imperatives.

1.2.3. Shift Towards Alternative Fuels

The transition toward alternative fuels represents a cornerstone of the shipping sector's strategy to reduce greenhouse gas emissions and meet increasingly stringent environmental standards. This shift is vital not only for enhancing the industry's sustainability but also for achieving fuel efficiency gains and mitigating its environmental footprint[22].
Among the alternative options, liquefied natural gas (LNG) currently leads the transition, being the most commercially mature solution[23]. LNG offers significant environmental benefits compared to conventional marine fuels, notably reducing emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x),

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[21] DNV. (2024, ottobre). *Emerging ship design principles for ammonia-fueled vessels*. Zero Carbon Shipping.
[22] https://maritime-professionals.com/the-potential-of-alternative-fuels-in-the-shipping industry/#:~:text=In%20conclusion%2C%20the%20shipping%20and,savings%20and%20reduced%20environmental%20impact.
[23] Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel*. International Council on Clean Transportation.

and particulate matter. It also contributes to lower CO_2 emissions, although concerns persist regarding methane slip—whereby unburned methane, a highly potent greenhouse gas, escapes into the atmosphere—thereby somewhat offsetting its overall climate advantages.
Biofuels are another promising alternative[24], as they can be integrated into existing engine systems with limited modifications. Derived from renewable biological sources, biofuels can substantially lower carbon emissions. Nevertheless, challenges related to the scalability and long-term sustainability of biofuel production remain areas of active research and development within the industry[25].
Hydrogen is also gaining prominence as a potential zero-emission fuel[26]. Produced from various sources, including renewable energy, hydrogen can be used in fuel cells to generate electricity for ship propulsion. However, technical challenges linked to hydrogen's storage—given its low density and the need for high-pressure or cryogenic systems—must be overcome. Furthermore, a widespread shift to hydrogen will require a significant expansion in the availability of green hydrogen, produced sustainably from renewable sources.
Ammonia, a carbon-free fuel, is increasingly[27] recognized for its potential role in shipping decarbonization. Its combustion does not release CO_2; however, to fully realize its environmental benefits, ammonia must be produced using renewable energy. Safety issues related to its toxicity and corrosiveness must also be carefully managed before large-scale adoption.
Additional alternatives under consideration include methanol, valued for its relative ease of storage and bunkering compared to LNG, as well as dimethyl ether (DME) and liquefied petroleum gas (LPG), both of which offer environmental improvements and are gaining interest as supporting technologies and infrastructures evolve[28].
In summary, the exploration of alternative fuels within the shipping sector reflects a dual commitment to environmental responsibility and operational efficiency. Although LNG remains the most established option today, the sector is rapidly advancing research and pilot projects across a range of fuels including biofuels, hydrogen, ammonia, methanol, DME, and LPG. Each fuel pathway entails specific advantages and challenges relating to emissions profiles, infrastructure requirements, safety considerations, and economic viability.

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[24] Marine Biodiversity. (2025). *Marine Biofuels Break Through: How Sustainable Algae Could Power Tomorrow's Ships*.
[25] IEA Bioenergy. (2017). *Biofuels for the marine shipping sector*.
[26] European Maritime Safety Agency (EMSA). (2023). *Potential of hydrogen as fuel for shipping*.
[27] International Chamber of Shipping (ICS). (2021). *A zero emission blueprint for shipping*. In collaboration with Ricardo.
[28] International Chamber of Shipping (ICS). (2021). *A zero emission blueprint for shipping*. In collaboration with Ricardo.

It is increasingly clear that no single solution will dominate. Instead, the industry is likely to embrace a multi-fuel model, tailoring fuel choices to vessel types, operational patterns, and geographic contexts. Achieving a widespread and effective transition will require coordinated efforts across the maritime value chain, supportive regulatory frameworks, expanded global refuelling infrastructure, and continuous innovation in engine and fuel storage technologies.

1.2.4. Supply Chain Resilience in the Shipping Industry

Supply chain resilience has emerged as a critical priority for the shipping sector, which faces a growing array of disruptive challenges ranging from natural disasters and geopolitical tensions to global pandemics. In this context, resilience refers to the supply chain's ability to anticipate, prepare for, absorb, adapt to, and recover from disruptions while maintaining the continuity of operations[29]. As highlighted by research published in *Transportation Research Part A: Policy and Practice*[30], four core dimensions characterize a resilient supply chain: robustness, redundancy, flexibility, and reorganization capacity. In the shipping industry, these dimensions translate into a range of strategic and operational measures:

1. Robustness involves strengthening infrastructure and operational protocols to withstand potential disruptions. Shipping companies are investing in more resilient assets, including vessels and port facilities, and enhancing cybersecurity systems to guard against digital threats.
2. Redundancy entails establishing backup systems and alternative options. In practice, this could include maintaining reserve vessels on critical routes, diversifying sourcing strategies, or securing access to multiple ports to ensure operational continuity even when specific nodes are disrupted.
3. Flexibility is crucial for adapting quickly to changing conditions. In shipping, flexibility is reflected in dynamic routing capabilities that allow vessels to modify their courses in response to weather patterns, congestion, or other unforeseen obstacles. Contractual flexibility and scalable operations further support the ability to adjust to fluctuating market demands.
4. Reorganization capacity refers to the industry's ability to swiftly redeploy resources, reconfigure logistics, and adapt staffing structures in response to disruptions, ensuring that recovery is rapid and effective.

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[29] https://www.sciencedirect.com/science/article/abs/pii/S0965856417301337
[30] Li, R., Ma, Z., Koutsopoulos, H. N., & Cats, O. (2024). Special issue in transportation research part A: Policy and practice evaluation of transport policy based on large-scale empirical data. *Transportation Research Part A: Policy and Practice*, *185*, Article 104100.

Technological innovation is playing an increasingly vital role in strengthening resilience. Tools such as big data analytics, artificial intelligence, and machine learning enhance forecasting accuracy and risk assessment capabilities, enabling proactive disruption management. In addition, blockchain technologies are being explored to improve the transparency and security of documentation processes, facilitating faster and more reliable resolution of operational issues.

Another fundamental aspect of resilience is supplying chain diversification. Expanding the supplier base and avoiding overreliance on single sources or routes allows shipping companies to better manage localized disruptions and sustain operations in volatile contexts.

Collaboration among supply chain stakeholders—including shippers, carriers, ports, and logistics providers—is essential for effective disruption management. Information sharing and coordinated response strategies significantly enhance the collective ability to withstand and recover from adverse events, often extending into joint recovery initiatives post-disruption.

Moreover, the shipping industry increasingly recognizes that sustainability and social responsibility initiatives contribute to resilience. Practices that foster environmental stewardship and strong community relationships not only strengthen corporate reputations but also provide strategic advantages during crises.

In conclusion, building supply chain resilience requires an integrated approach that spans infrastructure development, technological innovation, operational adaptability, and stakeholder collaboration. For an industry that forms the backbone of global trade, investing in resilience is not merely a strategic advantage but a fundamental necessity for ensuring the stability and reliability of international supply networks in an increasingly uncertain world.

1.2.5. Consumer Demand and E-commerce Growth

The expansion of e-commerce has profoundly transformed consumer behaviour, creating new dynamics and pressures for the shipping industry. The digitalization of commerce has elevated consumer expectations regarding product variety, immediate availability, and rapid delivery, thus reshaping the logistics and shipping sectors to meet these heightened demands for speed, reliability, and cost efficiency.

Insights from the *Journal of Operations Management*[31] highlight several key impacts of e-commerce growth on the shipping sector:

[31] Zhang, Y., Kuang, H., Wan, M., Zhang, M., & Li, J. (2025). Research on government subsidy strategy of green shipping supply chain considering corporate social responsibility. *Journal of Cleaner Production*, *435*, 140123.

1. Increase in Shipment Volumes: The convenience of online shopping has significantly boosted global shipping volumes. To accommodate this surge, the shipping industry has expanded fleet capacities, enhanced port infrastructure, and optimized routing strategies to manage the rising throughput of goods efficiently.
2. Complexity of Last-Mile Delivery: The final delivery phase, often referred to as the 'last mile,' has become increasingly critical and complex. Shipping companies are innovating through the development of urban distribution centres, the deployment of autonomous delivery vehicles and drones, and the implementation of advanced parcel tracking technologies to ensure faster and more efficient deliveries.
3. Growth of Reverse Logistics: The increase in online purchasing has led to a corresponding rise in product returns, requiring the establishment of effective reverse logistics systems. Efficient return management has become a key factor for customer satisfaction and operational profitability, involving integrated return planning and predictive analytics to manage return flows proactively.
4. Customization and Personalization: E-commerce has intensified consumer demand for personalized products and services, compelling the shipping sector to develop more flexible and responsive supply chains capable of accommodating a wide variety of products and tailored delivery requirements.
5. Environmental Sustainability Expectations: Growing consumer awareness of the environmental impacts associated with shipping activities has led to heightened demand for sustainable practices. Eco-friendly packaging, carbon-neutral shipping options, and other green initiatives are increasingly differentiating factors in a competitive marketplace.
6. Globalization of Demand Patterns: Online platforms have made products from around the world accessible to consumers everywhere, intensifying the globalization of demand. This trend necessitates efficient international logistics networks and the ability to manage complex cross-border shipping operations.
7. Predictive Analytics for Demand Management: Big data and predictive analytics are becoming crucial tools for forecasting demand, optimizing inventory management, and preparing for seasonal variations, enabling shipping companies to enhance operational efficiency and reduce associated costs.
8. Agility and Scalability: The highly volatile nature of e-commerce-driven demand requires shipping companies to maintain operational agility and scalability. Rapid adjustments to accommodate peak periods and demand fluctuations are essential for maintaining service levels and profitability.

Overall, the interplay between evolving consumer expectations and the rise of e-commerce has driven a transformative shift within the shipping sector[32]. It has necessitated major investments in technology and infrastructure, fostered new business models, and spurred innovation across logistics and supply chain management. To remain competitive in this dynamic environment, shipping companies must continue to adapt by embracing technological advancements, responding to shifting consumer preferences, and committing to sustainable and efficient operational practices.

1.2.6. Automation and Digitalization

Automation and digitalization are driving profound transformations within the shipping sector, representing a fundamental shift in vessel operations and the broader management of global trade. In a context where efficiency, safety, and sustainability are increasingly prioritized, the integration of advanced technologies is proving to be a decisive catalyst for change.

A study published in the *Journal of Shipping and Trade*[33] underscores the widespread impacts of automation and digitalization across various dimensions of the maritime industry. Onboard vessels, automation enhances navigational safety through sophisticated autopilot systems and advanced engine monitoring technologies, minimizing human error and enabling more precise control. Additionally, automated systems contribute to optimized fuel usage, predictive maintenance planning, and overall reductions in operational costs and environmental impacts.

Digitalization is equally reshaping industry practices. The adoption of cloud computing, Internet of Things (IoT) devices, and big data analytics supports real-time monitoring and management of shipping operations. This continuous flow of data is essential for enabling just-in-time (JIT) logistics, which aim to synchronize vessel arrivals with port service availability, thereby minimizing waiting times, cutting fuel consumption, and lowering associated emissions.

Blockchain technology is also gaining prominence in the digital transformation of shipping workflows. By ensuring secure, transparent, and tamper-resistant documentation, blockchain facilitates smoother customs processes and more reliable cargo tracking, reducing delays and minimizing the risk of fraud.

The deployment of these digital tools strengthens decision-making and risk management capabilities. Predictive analytics allow for early detection of potential maintenance issues, while artificial intelligence (AI) simulations enhance route planning, helping ships avoid adverse weather conditions and improve delivery reliability. Interestingly, climate tech project such as the Blue Visby Solution

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[32] https://www.sciencedirect.com/science/article/abs/pii/S0921344902000836

[33] https://jshippingandtrade.springeropen.com/articles/10.1186/s41072-020-00064-0

with a massive potential avoided GHG emission impact[34] are being developed. It is aimed at eradicating the single largest carbon inefficiency in maritime trade: the practice of ships that "sail fast, then wait" at the anchorage (SFTW). According to the work done by BVS and its consortium members, this represents about 15% of shipping GHG emissions. Eradicating SFTW will deliver GHG abatements that are equivalent to the emissions of an entire country the size of Norway. What makes this project different to a normal start-up is that its founders recognized that systemic change needs awareness and engagement from many stakeholders, and not simply selling a piece of tech. For that reason, they created a consortium of supporting companies and institutions, which has grown to 40+ members in just over two years[35]. This includes very large companies and the most prestigious institutions in the shipping sector.

Bureau Veritas (BV) conducted an independent technical review of Blue Visby's maritime optimization solution to validate its claims about fuel and emissions savings. The review examined how Blue Visby quantifies savings by comparing actual ship voyage data (including routes and speeds from AIS tracking) against optimized scenarios created by their algorithm. BV evaluated several key aspects: the methodology's robustness, data reliability, completeness of factors considered, and neutrality of results. They also assessed the accuracy of Blue Visby's digital twin simulations that model real-world shipping behaviours and optimization effects. The review confirmed that these simulations reliably reflect actual voyage conditions and emission reduction potential. The assessment aims to provide technical validation for regulators, ship owners, charterers, and other maritime industry stakeholders. Going forward, BV and Blue Visby have committed to continue analysing results from anonymized voyage samples, focusing on arrival time optimization as a practical decarbonization strategy. The goal is to provide the shipping industry with transparent, verifiable data demonstrating the system's environmental impact.[36]

A chart setting out the potential savings with the BVS solution is set out below:

[34] https://committees.parliament.uk/writtenevidence/106792/default/

[35] https://bluevisby.com/the-consortium/

[36] https://marine-offshore.bureauveritas.com/newsroom/bureau-veritas-validates-methodology-used-blue-visby-solution-estimate-its-effect-shipping

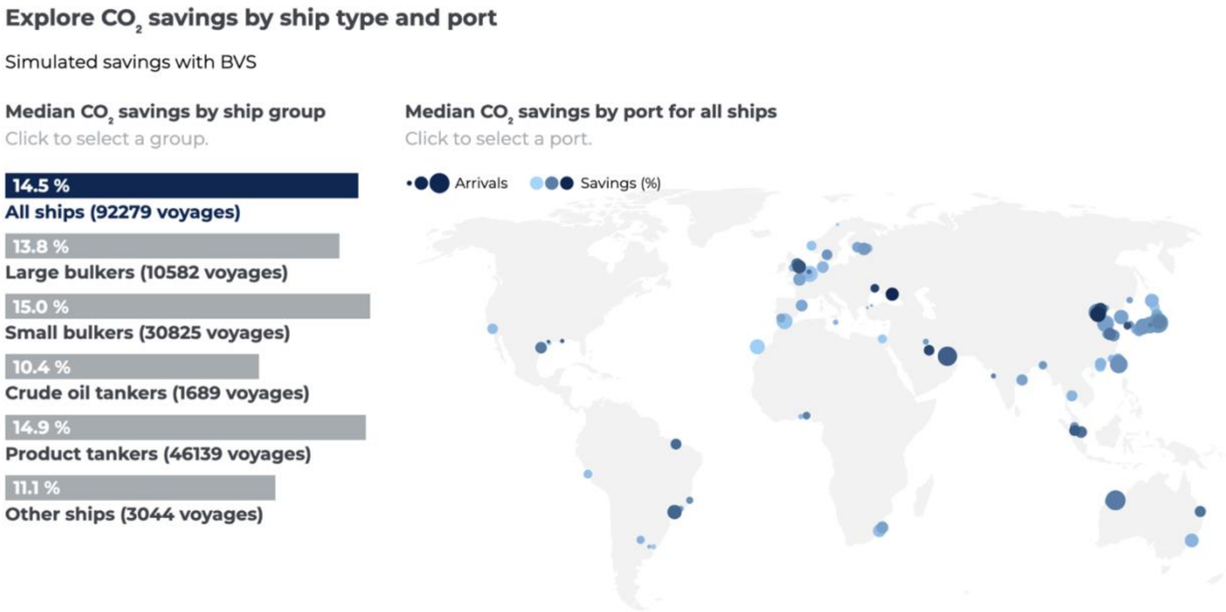

Chart 5 - Potential savings with BVS solution[37]

At port facilities, automation is revolutionizing cargo handling and storage operations[38]. Automated guided vehicles (AGVs), automated gantry cranes, and sophisticated sorting systems are significantly improving the speed and precision of container management, thereby enhancing port efficiency and reducing turnaround times. Integrated digital platforms further streamline communication among vessels, ports, and logistics providers, ensuring seamless coordination across the supply chain.

Nevertheless, the transition toward greater automation and digitalization presents several challenges. It demands substantial capital investments, targeted workforce training, and a fundamental redefinition of traditional operational roles. Moreover, the growing dependence on digital infrastructures heightens cybersecurity risks, necessitating the implementation of robust protective measures.

In conclusion, automation and digitalization are at the forefront of the shipping industry's modernization efforts. These technologies are enabling a new era of operational efficiency, safety, and environmental stewardship, fundamentally reshaping the structure of global supply chains. As the industry continues to evolve, the capacity to effectively adopt and leverage these technological innovations will be increasingly critical for maintaining competitiveness and achieving long-term success.

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[37] https://bluevisby.com/the-ghg-reductions/

[38] Farzadmehr, M., Carlan, V., Sys, C., & Vanelslander, T. (2023). Contemporary challenges and AI solutions in port operations: Applying Gale–Shapley algorithm to find best matches. *Journal of Shipping and Trade*, 8(1), 1–28

1.2.7. Economic Shifts Impacting Trade Volume

Economic fluctuations exert a profound influence on trade volumes within the shipping industry, closely mirroring broader trends in the global economy. As highlighted in an analysis published in *Energy*, various economic factors intertwine to shape the dynamics of maritime trade[39].

Global economic growth remains a fundamental driver of trade expansion. Periods of rising GDP are typically associated with an increase in the demand for imported goods and raw materials, whereas economic downturns tend to suppress consumer spending and industrial output, leading to a contraction in trade volumes. Exchange rate fluctuations also play a critical role: a stronger domestic currency may render a country's exports less competitive on the global market, thereby dampening trade flows, while a weaker currency can enhance export attractiveness by lowering relative prices.

Trade policies and international agreements significantly affect shipping patterns[40]. Protectionist measures, such as tariffs and import quotas, can restrict maritime trade, while the implementation of free trade agreements generally encourages trade by dismantling barriers and fostering greater market integration. Changes in industrial production and the relocation of manufacturing activities further impact trade dynamics, with the rise of manufacturing hubs in emerging economies stimulating regional trade flows and prompting the development of new shipping routes.

Commodity prices are another key determinant, particularly for bulk carriers. Elevated prices of raw materials tend to drive an increase in export volumes as producing countries capitalize on heightened demand, whereas declining commodity prices can suppress the volume of goods shipped internationally. In addition, the ongoing global energy transition is reshaping trade patterns: as countries progressively shift towards renewable energy sources, the demand for coal and oil transportation is expected to decline, affecting traditional bulk shipping markets.

Infrastructure development also plays a pivotal role[41]. Investments in port facilities, logistics hubs, and transportation networks can significantly enhance trade capacity, while infrastructure deficits can create bottlenecks that constrain trade growth. Although not purely an economic factor, technological advancements have substantial economic implications by increasing the efficiency of logistics operations, reducing transit times, and enabling higher volumes of goods to move through global supply chains. Consumer behaviour, deeply influenced by economic confidence and uncertainty, likewise affects trade volumes. In times of economic optimism, increased consumer spending

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[39] https://www.sciencedirect.com/science/article/abs/pii/S0360544221017953

[40] World Bank Blogs. (2023). *Why ports matter for the global economy*. https://blogs.worldbank.org/en/transport/why-ports-matter-global-economy

[41] Saeed, N., & Larsen, O. I. (2018). The impacts of port infrastructure and logistics performance on economic growth: The mediating role of seaborne trade. *Journal of Shipping and Trade, 3*(1), 1–19.

typically stimulates import and export activity, whereas periods of uncertainty or recession tend to dampen consumer demand and contract trade flows. Financial markets and investment trends further shape trade volumes indirectly: strong investment in certain sectors can lead to production booms and greater shipping needs, while capital shortages can have the opposite effect, slowing industrial output and diminishing trade.

In conclusion, economic shifts—ranging from macroeconomic growth trends and currency movements to trade policy developments, commodity price fluctuations, and evolving consumer behaviours have both direct and indirect repercussions on maritime trade volumes. For the shipping industry, maintaining operational agility and strategic foresight is essential to effectively navigate the complexities of an ever-changing global economic landscape.

1.2.8. Crew Welfare and Labor Standards in the Shipping Industry

Crew welfare and labour standards represent critical dimensions of the shipping industry, influencing not only the well-being of seafarers but also the overall efficiency, safety, and public perception of maritime operations. A study published by the *Social Science Research Network* highlights the importance of protecting the rights and health of maritime workers, a task made complex by the isolated nature of their working environment and the jurisdictional challenges posed by international waters[42]. There is a growing recognition across the industry that safeguarding crew welfare is essential to ensuring operational effectiveness. Seafarers who work in safe, supportive environments, and who benefit from fair treatment and adequate rest, are better equipped to perform their duties with diligence and precision, thereby reducing the risk of accidents and promoting smoother operations. In contrast, neglecting crew welfare can lead to a range of problems, including diminished morale, higher staff turnover, operational inefficiencies, and, in severe cases, strikes or legal disputes that can seriously damage a company's reputation and bottom line.

Efforts to enhance seafarer welfare encompass multiple aspects, including the provision of fair wages, reasonable working hours, access to quality medical care, and the supply of nutritious food onboard. Attention to mental health is also becoming increasingly important, recognizing the psychological strains caused by prolonged periods at sea, isolation from family, and the stressful conditions often encountered during voyages. In response, companies are expanding access to recreational activities, offering improved communication links with loved ones, and developing comprehensive mental health support programs.

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[42] https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2923359

Adherence to international labour standards, particularly those established by the Maritime Labour Convention (MLC)[43], remains a central pillar in promoting crew welfare. The MLC codifies the fundamental rights of seafarers across a wide spectrum of issues, including accommodation standards, recreational facilities, food quality, healthcare services, and social security protections. Compliance with these regulations requires shipping companies not only to implement appropriate measures but also to demonstrate their effectiveness through inspections and formal certifications.

Beyond regulatory requirements, there is a strong business rationale for prioritizing crew welfare. Companies known for high labour standards are more attractive to skilled maritime professionals and enjoy a competitive advantage in the labour market. Strong welfare practices also facilitate compliance with international due diligence expectations and foster positive relationships with ports, regulatory bodies, and customers.

Moreover, in an era of instantaneous communication and heightened public scrutiny, reputational risks linked to labour abuses are significant. Reports of poor treatment can quickly damage a company's standing among consumers and business partners alike. The emerging trend of ethical shipping—where stakeholders consider the social responsibility practices of transport providers in their purchasing decisions—further underscores the importance of maintaining exemplary labour standards. To meet these expectations, many shipping companies are investing not only in technical training programs but also in education initiatives that promote awareness of workers' rights and personal health. Some industry leaders are proactively establishing policies that go beyond compliance, setting new benchmarks for best practices in crew welfare.

In conclusion, the protection of seafarers' welfare and the enforcement of high labor standards are not merely moral imperatives or regulatory obligations; they are essential components of the shipping industry's long-term sustainability, operational excellence, and public legitimacy. Upholding these standards is therefore a critical priority for any company committed to responsible and future-oriented growth.

1.2.9. Investor and Shareholder Activism in the Shipping Industry

Investor and shareholder activism is emerging as a powerful driver of change within the shipping industry, reflecting a broader trend where stakeholders are increasingly influencing corporate governance and sustainability practices. Research published in *Transportation Research Part E: Logistics and Transportation*[44] *Review* highlights how investors and shareholders are placing growing

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[43] International Chamber of Shipping. (2020). *Welfare aspects of the Maritime Labour Convention, 2006*

[44] Transportation Research Part E: Logistics and Transportation Review. *ScienceDirect*. Retrieved May 31, 2025.

emphasis on environmental, social, and governance (ESG) criteria, pressuring shipping companies to adopt more responsible and sustainable business models. This growing activism stems from a heightened awareness of the long-term risks associated with environmental degradation, social inequalities, and poor governance structures. Investors recognize that companies addressing these challenges are better positioned for stable, long-term performance. As a result, they are pushing shipping companies to make concrete improvements in key areas such as carbon emissions reduction, energy efficiency, and labour rights. They are also evaluating how well firms are prepared for upcoming regulatory shifts, particularly those linked to environmental protection and climate resilience. Engagement strategies often involve direct dialogue with corporate management, aiming to encourage voluntary improvements before resorting to more public actions like submitting shareholder proposals. Increasingly, investors are joining forces through coalitions, amplifying their collective influence and enhancing their ability to drive significant corporate changes.

Public campaigns represent another tool employed by activist shareholders. By engaging broader groups—including regulators, other investors, and the public—through shareholder meetings, media outreach, and detailed reports, activists seek to generate widespread support for their initiatives. The impact of such activism is visible in the growing number of shipping companies committing to ambitious decarbonization targets and implementing comprehensive sustainability strategies, not merely in response to regulatory pressures, but also to align with investor expectations for resilient and future-ready business models[45]. Institutional investors, due to their size and market presence, play a particularly important role in this transformation. Their considerable shareholdings provide them with substantial leverage, and there is increasing expectation from their own stakeholders for proactive engagement on ESG issues. These investors also recognize that companies failing to address sustainability risks may face declining access to capital, as financial institutions and credit markets integrate ESG considerations into their investment and lending criteria.

In conclusion, investor and shareholder activism is becoming an influential force in reshaping the shipping industry's trajectory. By exerting their influence, investors not only protect the value of their investments but also contribute to the sector’s ability to adapt to a rapidly evolving business environment where sustainability and corporate responsibility are central to long-term success.

1.2.10. Stricter Waste Management and Recycling Policies.

Waste management and recycling policies are assuming an increasingly central role within the maritime industry, driven by heightened environmental concerns and evolving regulatory

[45] https://www.sciencedirect.com/science/article/abs/pii/S0308597X16308545

frameworks. Research published in *Marine Policy* and studies from the Norwegian University of Science and Technology highlight a significant shift toward more sustainable practices, reflecting both regulatory pressures and industry-led initiatives[46]. The shipping sector is being called upon to enhance its waste management strategies across the entire lifecycle of maritime operations, from onboard practices to port infrastructure and ship recycling processes. The International Maritime Organization (IMO) has been instrumental in setting international standards, particularly through the MARPOL Convention, which establishes stringent regulations aimed at preventing marine pollution and ensuring proper waste handling procedures. A key focus is the improvement of onboard waste management. New requirements oblige ships to adopt comprehensive waste segregation systems, maintain meticulous documentation of waste handling activities, and implement measures to minimize waste generation. Enhanced onboard treatment technologies and systematic disposal processes at designated port facilities are becoming standard expectations.

Simultaneously, ports are under increasing obligation to provide sufficient reception facilities capable of handling the diverse waste streams produced by ships. Ensuring the availability of efficient waste processing services at ports is essential for preventing the improper disposal of waste into marine ecosystems. Ship recycling practices are also undergoing significant reform. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships—although not yet in force—sets out requirements to ensure that ship dismantling activities do not endanger human health or the environment[47]. Emphasis is placed on the responsible management of hazardous materials and the recycling of valuable ship components in a sustainable manner.

Plastic waste management has emerged as a particular priority, aligning with global efforts to curb oceanic plastic pollution. The IMO advocates for substantial reductions in plastic usage and improved disposal practices within the shipping sector[48].

Furthermore, the principles of the circular economy are increasingly being integrated into maritime waste management strategies[49]. Innovations in recycling technologies and resource recovery processes are encouraging the reuse of materials generated by ship operations, reducing environmental impacts and contributing to resource efficiency. The practice of green shipbreaking is gaining traction, urging shipowners to consider the environmental and safety standards of ship

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[46] https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2400612

[47] International Maritime Organization. *Recycling of ships and the Hong Kong Convention*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Recycling-of-ships-and-Hong-Kong-Convention.aspx

[48] International Maritime Organization. *Action on plastics*. International Chamber of Shipping.

[49] Notteboom, T., Pallis, A., & Rodrigue, J.-P. *Chapter 3.5 – Ports and the Circular Economy*. Port Economics, Management and Policy.

dismantling facilities. Despite potentially higher costs, selecting responsible recycling options is becoming an important element of corporate sustainability strategies.

Economic instruments are also being explored as mechanisms to promote better waste management behaviours. These include the introduction of disposal fees or incentives aimed at minimizing waste generation and encouraging environmentally responsible practices.

Collectively, these developments point toward a future in which waste management and recycling are governed by a comprehensive and increasingly rigorous regulatory framework. This shift is motivated not only by the imperative to protect marine ecosystems but also by the recognition that efficient waste management can yield cost savings, enhance corporate reputations, and ensure compliance with tightening international standards.

In response, shipping companies are investing in crew training programs, upgrading waste management technologies, and revising operational protocols to align with new requirements. By doing so, they are not only addressing current regulatory demands but also positioning themselves for success in an industry where sustainability will be ever more central to operational excellence and competitive advantage.

1.2.11. Insurance and Liability Considerations.

Insurance and liability issues within the maritime sector are becoming increasingly complex, particularly considering growing environmental concerns and the advent of new technologies. Insights from *Shipping and the Environment: Law and Practice* and *Ship Operations: New Risks, Liabilities and Technologies in the Maritime Sector*[50] offer a detailed exploration of these evolving challenges.

The heightened focus on environmental protection has significantly reshaped the maritime insurance landscape. Insurers are now paying closer attention to the environmental policies and preparedness of shipping companies, particularly regarding liabilities linked to pollution and ecological damage. Coverage must account for a broad range of potential liabilities, including the costs of environmental remediation, compensation for third-party damages, and the imposition of legal penalties. Consequently, shipping operators are increasingly required to maintain comprehensive insurance policies that cover incidents such as oil spills, the improper disposal of hazardous waste, and other pollution-related events.

[50] Soyer, B., & Tettenborn, A. (Eds.). (2022). *Ship operations: New risks, liabilities and technologies in the maritime sector*. Routledge.

The integration of emerging technologies, particularly automation and the development of autonomous vessels, introduces additional layers of complexity to the allocation of risks and liabilities[51]. In this context, liability risks are shifting from human error towards technological failures and vulnerabilities, including cyberattacks. As legal and regulatory frameworks continue to evolve in response to these technological advancements, insurance products must adapt accordingly to accurately reflect the distribution of risks across new operational models. Climate change represents another critical factor influencing maritime insurance. Rising frequencies of extreme weather events contribute to heightened risks of navigational accidents, cargo damage, and salvage operations, all of which must be integrated into insurers' risk assessment models and pricing structures. The growing unpredictability of environmental conditions necessitates increasingly sophisticated risk evaluation tools within the insurance industry. Ship recycling activities also bring notable liability considerations[52]. Shipping companies must ensure that end-of-life vessel dismantling processes adhere to international and domestic environmental and safety standards. Non-compliance exposes firms to significant legal and financial liabilities, emphasizing the need for insurance coverage that extends beyond traditional operational risks to encompass responsibilities tied to environmental stewardship.

Moreover, the increased emphasis on corporate social responsibility and the rise in litigation concerning environmental and social matters have amplified the importance of liability insurance. Companies must now protect themselves not only against conventional navigational risks but also against reputational damage and legal claims arising from environmental and human rights concerns. In addition, the shipping industry's shift toward decarbonization is likely to stimulate the emergence of new insurance products related to carbon trading schemes, carbon credits, and emissions-related liabilities. As regulatory frameworks governing carbon emissions tighten, companies may need to secure additional coverage to manage the financial risks associated with compliance failures or penalties tied to environmental regulations[53].

In conclusion, the evolving complexity of insurance and liability considerations in the shipping industry reflects a broader transformation driven by environmental imperatives, technological innovation, and shifting legal standards. To navigate these challenges successfully, shipping companies must engage closely with insurers to design comprehensive risk management strategies,

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[51] Hvassallo. (2024). *Autonomous Ships and Liability Issues: Maritime Law Will Need to Evolve*.
[52] DNV. (2023)*How to ensure ESG-compliant ship recycling*.
[53] Britannia P&I. (2025). *Climate change, severe weather and its impact on shipping risks*.

while insurers must continue to innovate, offering products that anticipate and address the dynamic nature of maritime operations.

1.2.12. Piracy and Maritime Security

Piracy and broader maritime security challenges continue to represent significant risks for the shipping industry, requiring a comprehensive and evolving approach to risk management. Research from the *Journal of Terrorism Research* and insights from *Maritime Security – Perspectives for a Comprehensive Approach*[54] highlight how the nature of threats at sea has developed and how the sector is adapting its strategies to mitigate them[55].

The threat posed by piracy is not uniform across global waters; rather, it varies considerably by region. In areas such as the Gulf of Guinea, piracy often takes the form of opportunistic attacks by small groups, while off the coast of Somalia, operations have tended to be more organized and sophisticated. These criminal activities not only endanger the lives and safety of seafarers but also result in significant financial losses stemming from ransom payments, damaged cargo, and shipment delays.

In response, the shipping industry has adopted a range of preventive and protective measures. One such strategy is the deployment of armed security personnel on board vessels traversing high-risk zones, a practice that has proven effective in deterring pirate attacks and reassuring both crew members and operators. Additionally, the sector has embraced Best Management Practices (BMP), which provide practical guidelines for vessels to minimize risk. These include measures such as maintaining high cruising speeds, employing water cannons to prevent boarding attempts, and fortifying ships against unauthorized access.

International cooperation has been crucial in enhancing maritime security. Joint naval patrols and the creation of monitored transit corridors have significantly reduced the incidence of attacks, illustrating the value of coordinated global efforts. Strengthened legal and regulatory frameworks have also played an essential role by establishing clear rules of engagement and facilitating the prosecution of individuals involved in piracy.

Information sharing and timely reporting of incidents have become central components of the industry's defence strategy. By exchanging data on emerging threats, shipping companies can better anticipate risks and tailor their security measures accordingly. Technological advancements, such as the use of surveillance drones and advanced radar systems, have further improved early threat detection capabilities, allowing crews to respond proactively to potential dangers.

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[54] Feldt, L., Roell, P., & Thiele, R. D. (2013). *Strategic options for the future maritime security environment*. ISPSW Strategy Series: Focus on Defense and International Security.

[55] https://www.sciencedirect.com/science/article/abs/pii/S1366554518302357

Crew preparedness has equally advanced[56], with enhanced training programs now routinely including piracy response drills, especially for those operating along high-risk routes. Despite these efforts, the threat persists, often exacerbated by the political instability and economic hardship prevalent in some coastal regions where piracy originates.

Maritime security concerns extend beyond piracy alone, encompassing issues such as smuggling, human trafficking, and illegal fishing. Addressing these challenges requires an integrated, multi-faceted approach that combines legal, diplomatic, military, and private sector initiatives. A comprehensive strategy must also recognize and address the underlying causes of maritime insecurity, including political conflict and socio-economic disparities, to foster long-term regional stability.

In conclusion, piracy and broader maritime security threats demand continuous vigilance, adaptability, and collaboration within the shipping industry. By reinforcing preparedness, strengthening international partnerships, and adopting robust legal and technological measures, the industry strives to safeguard vessels, protect crews, and ensure the resilience of global maritime trade.

1.2.13. Impact of Climate Change on Sea Routes

The effects of climate change on maritime routes are becoming increasingly evident, with profound implications for the global shipping industry. Research published in *Wiley Interdisciplinary Reviews: Climate Change* and *Scientific Reports*[57] highlights how shifting climatic conditions are altering navigational patterns and the accessibility of strategic sea passages.

One of the most visible consequences is the accelerated melting of Arctic ice, which is progressively opening previously inaccessible routes such as the Northern Sea Route and the Northwest Passage[58]. These emerging pathways offer significantly shorter transit distances between Asia, Europe, and North America, potentially leading to reductions in fuel consumption, shipping costs, and congestion on traditional routes like the Suez and Panama Canals.

Despite these advantages, the opening of Arctic Sea lanes introduces a series of new challenges. Navigational risks are heightened due to the unpredictable presence of drifting icebergs and rapidly changing ice conditions. Ships operating in these waters must be equipped with reinforced hulls, advanced navigational systems, and highly trained crews capable of handling extreme environments. Furthermore, the Arctic's ecological sensitivity raises serious environmental concerns. Increased

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[56] Interpol. *The Maritime Security Programme*. https://www.interpol.int/en/Crimes/Maritime-crime/The-Maritime-Security-Programme

[57] Wu, J., Zhao, Y., Du, S., Wu, W., Chen, Z., & Yang, S. (2024). Climate change impacts on maritime shipping emissions. *Scientific Reports*, *14*(1), Article 53308

[58] https://www.nature.com/articles/s41598-024-53308-5

shipping activity poses threats to fragile marine ecosystems, emphasizing the urgent need for stringent environmental regulations and effective spill response mechanisms in these remote regions.

The limited availability of search and rescue (SAR) infrastructure in the Arctic further complicates matters. With growing maritime traffic, ensuring the safety of seafarers necessitates the development and expansion of SAR capabilities across the region.

Geopolitical tensions are another emerging issue[59], as the opening of Arctic routes invites competition among nations asserting control and sovereignty claims. Disputes over navigational rights and territorial boundaries could heighten diplomatic tensions, necessitating careful international negotiations and cooperative governance frameworks. Beyond the Arctic, climate change is influencing maritime operations on a global scale. The increasing frequency and severity of storms, along with shifting ocean currents, are disrupting traditional shipping lanes and schedules, heightening operational risks and causing delays. To adapt, shipping companies must invest in enhanced weather forecasting technologies, flexible routing strategies, and vessel designs capable of withstanding more extreme conditions. Rising sea levels also pose a significant threat to port infrastructure worldwide. Ports will need to undertake long-term adaptation measures, such as elevating docks and reinforcing coastal defences, to ensure resilience against future climatic impacts.

In conclusion, climate change is reshaping the maritime landscape, simultaneously creating new opportunities and introducing complex risks for the shipping industry. While the opening of new sea routes may offer economic advantages, they come with substantial environmental, operational, and geopolitical challenges. Adapting to these realities will require continuous innovation, stronger international collaboration, and a commitment to sustainable and resilient maritime practices in an era defined by a warming planet.

1.2.14. Ballast Water and Biofouling Management in the Shipping Industry

Ballast water and biofouling management have emerged as critical environmental challenges for the maritime industry, primarily due to their role in the spread of invasive aquatic species across global ecosystems. Analyses from *Marine Policy* and *Global Maritime Transport and Ballast Water Management – Issues and Solutions* provide a comprehensive exploration of these complex issues, and the strategies employed to address them[60].

Ballast water is fundamental to ensuring the stability and safe operation of ships during voyages. However, it also represents a major vector for the unintended transfer of marine organisms. Water

[59] International Maritime Organization. (2022). *Navigating climate change: Arctic shipping and global impacts*.
[60] https://www.sciencedirect.com/science/article/abs/pii/S0308597X15003590

loaded in one geographic area, often containing local flora and fauna, can release non-native species into distant ecosystems where they may lack natural predators, potentially disrupt local biodiversity and causing considerable ecological and economic harm.

To mitigate these risks, the International Maritime Organization (IMO) introduced the Ballast Water Management Convention[61], establishing regulatory requirements for minimizing the transfer of harmful aquatic organisms and pathogens. Ships must comply with these standards through several key approaches. The installation of onboard ballast water treatment systems is now widespread, using technologies such as ultraviolet radiation, filtration, or chemical disinfection to neutralize invasive species before discharge. An alternative method involves ballast water exchange, where ships replace their ballast water in mid-ocean regions with lower ecological risk, although this method has limitations related to water quality and sediment presence. Moreover, all vessels must maintain comprehensive Ballast Water Management Plans, document procedures and ensuring regulatory compliance during operations.

Biofouling, the accumulation of marine organisms on submerged surfaces of vessels, constitutes another major pathway for the global dispersal of non-native species. Organisms adhering to ship hulls can be transported across oceans, introducing new species into foreign ecosystems. To combat biofouling, ships increasingly employ anti-fouling coatings designed either to prevent organism attachment or to facilitate easier removal. Regular hull cleaning and maintenance are also essential strategies, serving the dual purpose of minimizing the ecological risks associated with species transfer and improving vessel fuel efficiency by reducing hydrodynamic drag. Additionally, guidelines promoting the development and implementation of Biofouling Management Plans are gaining traction, encouraging proactive maintenance practices across the industry.

Effective ballast water and biofouling management require the collaboration and commitment of all maritime stakeholders. Balancing environmental protection with operational and economic considerations remains a key challenge. Continuous research and innovation aim to enhance existing treatment technologies and develop more efficient, cost-effective anti-fouling solutions, reflecting the industry's dedication to improving its environmental performance.

In conclusion, the management of ballast water and biofouling represents a vital component of the maritime industry's environmental stewardship efforts. Through compliance with international regulations, technological advancements, and proactive management practices, the shipping sector is

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[61] International Maritime Organization. (2004). *International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention)*.
Retrieved from https://www.imo.org/en/OurWork/Environment/Pages/BallastWaterManagement.aspx.

actively working to prevent the spread of invasive species, safeguard marine biodiversity, and contribute to the sustainable future of global maritime operations.

1.2.15. Partnerships with the Energy Sector.

Collaborations between the shipping industry and the energy sector are becoming increasingly vital for advancing sustainable and efficient maritime operations. Research findings presented in *The Role of Natural Gas and Its Infrastructure in Mitigating Greenhouse Gas Emissions, Improving Regional Air Quality, and Renewable Resource Integration* (Springer)[62] and *Energy Research & Social Science*[63] underscore the strategic importance and multifaceted benefits of these partnerships.

The urgency to reduce greenhouse gas emissions and improve air quality, in line with international environmental targets and societal expectations, is a key driver behind these initiatives. As a major consumer of fossil fuels, the shipping sector is seeking pathways to lower its carbon footprint, while the energy sector is expanding its efforts to deploy cleaner energy sources and build the supporting infrastructure necessary for a low-carbon economy.

One of the prominent areas of collaboration is the promotion of liquefied natural gas (LNG) as a marine fuel. Shipping companies are working alongside energy providers to transition from traditional heavy fuel oil to LNG, a cleaner-burning alternative. This shift necessitates the development of extensive LNG bunkering facilities at ports and the construction or retrofitting of LNG-powered vessels. In parallel, efforts are underway to integrate renewable energy sources, such as solar and wind power, into maritime operations. Partnerships with energy firms are essential to develop hybrid propulsion systems that combine conventional fuels with renewable energy, enhancing the sustainability profile of shipping fleets.

Advancements in energy storage technologies, particularly in battery systems, are also a focus of these collaborations. Improved energy storage is critical for the electrification of short-sea shipping and port operations, and joint efforts are crucial for scaling these technologies to meet maritime demands. Another promising area of cooperation lies in carbon capture and utilization (CCUS) technologies. Energy companies, with their expertise in carbon management, are supporting the adaptation of onboard carbon capture systems to mitigate emissions directly from vessels.

The exploration of hydrogen and ammonia as future zero-emission marine fuels further exemplifies the synergy between the two sectors. The production of green hydrogen and ammonia, as well as the establishment of associated supply chains, relies heavily on energy sector capabilities and

[62] https://link.springer.com/chapter/10.1007/978-3-319-74454-4_10
[63] https://www.sciencedirect.com/science/article/pii/S2214629623004267

investments. Joint ventures and the creation of innovation hubs are accelerating the development of clean energy solutions tailored specifically to the needs of maritime transport. Moreover, through coordinated advocacy, shipping and energy stakeholders are influencing policy development, seeking incentives, and securing funding to support research, technological innovation, and infrastructure expansion. Importantly, these partnerships enable a shared approach to investment and risk management. By pooling expertise and financial resources, shipping companies and energy providers can more effectively navigate the challenges associated with developing and deploying new technologies.

In conclusion, the collaboration between the shipping and energy sectors represents a cornerstone of the broader decarbonization agenda. These partnerships are not only transforming both industries but are also setting a precedent for cross-sector cooperation in the pursuit of a more sustainable and resilient global economy.

1.2.16. Green Financing and Incentives.

Green financing and incentive mechanisms are playing an increasingly central role in promoting environmental sustainability within the shipping industry. Research from the University of the Aegean[64] and findings published in the *Maritime Business Review*[65] highlight how financial instruments are crucial in supporting the sector's transition toward more eco-friendly and resilient practices.

Green financing refers to a suite of financial services and products specifically designed to fund projects that contribute positively to environmental outcomes. In the maritime sector, this typically involves supporting initiatives such as the construction of low-emission vessels or the installation of advanced pollution control technologies. Among the key instruments, green bonds stand out as a vital funding source: these bonds are issued by companies to raise capital for environmentally focused projects, enabling the financing of new shipbuilding projects incorporating eco-efficient technologies or retrofitting older fleets with cleaner propulsion systems.

Sustainability-linked loans represent another important tool, providing financial incentives tied to the achievement of specific environmental performance targets. In these agreements, interest rates are adjusted based on a shipping company's success in meeting criteria such as reductions in carbon dioxide emissions. Innovative leasing models also contribute to expanding access to green vessels, offering operators the opportunity to use environmentally advanced ships without the need for

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[64] https://hellanicus.lib.aegean.gr/handle/11610/23406
[65] https://www.emerald.com/insight/content/doi/10.1108/MABR-08-2018-0030/full/html

substantial initial capital investment, often incorporating incentives for achieving environmental goals. Public grants and subsidies are equally crucial, easing the financial burden associated with adopting clean technologies by offsetting high upfront costs. Participation in carbon credit schemes further offers a market-driven incentive structure, where companies that successfully reduce emissions can trade credits, fostering broader sector-wide emission reductions. Additionally, risk-sharing mechanisms, whereby public and private actors jointly assume the financial risks associated with adopting innovative technologies, encourage investments in new, less proven environmental solutions.

Regulatory incentives complement financial tools by directly rewarding environmentally responsible behaviour. Ports may reduce fees for vessels that demonstrate superior environmental performance, including lower emissions or reduced noise pollution. Similarly, ships that meet high environmental standards may benefit from operational advantages such as priority berthing, resulting in both environmental and economic benefits. Emission Control Areas (ECAs) enforce stricter emissions standards in designated regions, with compliant ships potentially eligible for additional financial or operational incentives. Certification programs that recognize exemplary environmental practices further enhance competitiveness by appealing to an increasingly eco-conscious customer base.

The growing integration of green financing and regulatory incentives within the maritime industry signals a fundamental shift towards aligning financial strategies with sustainability objectives. By leveraging these mechanisms, shipping companies are better equipped to accelerate the transition toward sustainable operations, simultaneously meeting evolving market expectations and contributing to global environmental goals. It is increasingly evident that green finance not only supports but actively rewards the sector's commitment to building a cleaner and more resilient maritime future.

1.2.17. Environmental Advocacy and NGO Influence.

Environmental advocacy and the growing influence of non-governmental organizations (NGOs) are playing a transformative role in reshaping the practices and governance structures of the shipping industry. Drawing on the works of Raul Pacheco-Vega, Amanda Murdie, research from the Liu Institute for Global Issues at the University of British Columbia[66], and literature published in *Global Environmental Politics*[67], it becomes clear that NGOs have become pivotal actors in promoting environmental accountability within global maritime operations.

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[66] https://www.taylorfrancis.com/chapters/edit/10.4324/9781003213321-10/environmental-ngos-work-test-conditional-effectiveness-environmental-advocacy-raul-pacheco-vega-amanda-murdie

[67] https://direct.mit.edu/glep/article-abstract/10/4/36/14474/NGO-Power-in-Global-Social-and-Environmental.

NGOs have proven highly effective in elevating environmental issues within public discourse and corporate agendas. Employing a variety of strategies—including lobbying for stricter regulations, engaging directly with industry leaders, and mobilizing public support through awareness campaigns—they act as critical watchdogs, monitoring corporate behaviour and demanding higher environmental standards. The effectiveness of NGO advocacy, however, is often conditioned by contextual factors such as the prevailing political climate, the strength of partnerships with other sectors, and the degree of public concern about environmental matters. Their influence tends to be amplified when supported by broad societal backing and when constructive engagement with corporate stakeholders is possible.

In the maritime sector specifically, environmental NGOs have been particularly active in pushing for reductions in greenhouse gas emissions, preventing marine pollution, and advocating for the protection of ocean biodiversity. Their efforts have led to meaningful regulatory advancements, such as the adoption of cleaner fuel standards under International Maritime Organization (IMO) directives and the creation of Emission Control Areas (ECAs) aimed at limiting air pollution from ships[68].

NGOs have also played a central role in advancing Corporate Social Responsibility (CSR) initiatives within the shipping industry[69]. By emphasizing the importance of sustainable practices, they have encouraged companies to integrate environmental considerations into their business models. As a result, many shipping companies have invested in fuel-efficient technologies, adopted operational practices such as slow steaming to reduce emissions, and participated in environmentally responsible ship recycling programs.

Moreover, the influence of NGOs extends beyond direct engagement with companies to shaping broader consumer and investor behaviours. As environmental awareness grows among the public, stakeholders are increasingly making decisions based on a company's environmental track record. This shift has incentivized shipping firms to seek certifications, participate in voluntary sustainability programs, and visibly demonstrate their commitment to responsible environmental stewardship.

Research from the University of British Columbia[70] emphasizes that CSR in the shipping sector is increasingly driven not just by regulatory compliance but also by the desire to meet the expectations of investors, customers, and society at large. CSR initiatives now often include measures to enhance

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[68] Lloyd's Register. (2025, May). *05/2025: New Emissions Control Areas*. Retrieved from https://www.lr.org/en/knowledge/class-news/05-25/

[69] Transport & Environment. (2025, January). *NGO calls for shipping to slow down*. Retrieved from https://www.worldcargonews.com/shipping-logistics/2025/01/ngo-calls-for-shipping-to-slow-down/

[70] Coady, L., Strandberg, C. and Ota, Y. (2013) *THE ROLE OF CORPORATE SOCIAL RESPONSIBILITY (CSR) IN THE INTERNATIONAL SHIPPING SECTOR*

energy efficiency, lower carbon footprints, and contribute positively to the communities affected by shipping operations.

In conclusion, environmental NGOs have become influential and indispensable stakeholders in the maritime sector. Through persistent advocacy, strategic partnerships, and the ability to mobilize public support, they have significantly advanced the cause of environmental sustainability within the industry. Their work has reinforced the critical role of Corporate Social Responsibility, encouraging shipping companies to adopt more sustainable, transparent, and forward-looking business models.

1.2.18. Technological Advances in Port and Logistics Operations

Technological innovation is profoundly transforming port and logistics operations, substantially improving the efficiency, safety, and sustainability of the global shipping industry. Research published in the *International Journal of Maritime Economics*, alongside broader literature on the subject, emphasizes the scale and impact of these advancements[71].

One of the most notable developments is the automation of port activities. Automated Guided Vehicles (AGVs) and automated cranes are increasingly employed to manage the loading and unloading of cargo, reducing vessel turnaround times and enhancing workplace safety by limiting human exposure to hazardous operations. Automation also extends to container management, where sophisticated systems ensure optimal placement and organization of cargo, both on board ships and within port storage facilities, thereby maximizing space utilization and operational efficiency.

Digitalization, coupled with the power of big data analytics and the Internet of Things (IoT), is further reshaping port operations. Real-time data collection and analysis enable predictive maintenance of equipment, more efficient cargo handling, and improved management of port traffic. IoT devices, such as sensors installed on containers, offer continuous cargo monitoring, ensuring product integrity and facilitating the seamless flow of goods throughout the supply chain.

Blockchain technology is also gaining ground in maritime logistics, providing a secure, transparent, and tamper-proof method for tracking transactions and cargo movements. By creating immutable records, blockchain reduces the need for extensive paperwork, accelerates customs clearance processes, and mitigates the risk of fraud, thereby enhancing the overall reliability and efficiency of the logistics chain. Artificial Intelligence (AI) and machine learning algorithms are being applied to diverse aspects of port operations, from predictive maintenance planning to the optimization of cargo handling strategies. These technologies process vast datasets to identify patterns and anticipate operational issues, enabling better-informed decision-making and more proactive management.

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[71] https://link.springer.com/article/10.1057/palgrave.ijme.9100003

Environmental sustainability is becoming a central focus, with the adoption of green technologies aimed at minimizing emissions and energy consumption. The electrification of port machinery and vehicles, coupled with the integration of renewable energy sources like solar and wind power, exemplifies this shift. Additionally, ports are investing in shore power systems, allowing docked vessels to connect directly to the electrical grid and shut down their engines, significantly reducing air pollution. The concept of the "smart port"[72] encapsulates the integration of these various technologies into a unified, intelligent operational environment. Smart ports combine automation, digitalization, and environmental innovations to create highly efficient, sustainable, and secure logistics hubs, offering a blueprint for the future evolution of the maritime sector. Technological progress is also enhancing collaboration across the logistics chain. Digital platforms are improving communication and information sharing among shipping companies, port authorities, customs agencies, and other stakeholders, leading to better coordination, faster operations, and fewer delays[73]. In conclusion, the technological modernization of port and logistics operations is driving a fundamental transformation in the shipping industry. By embracing automation, digital technologies, and sustainability-focused initiatives, ports are becoming more efficient, resilient, and environmentally responsible. These advancements not only strengthen operational capabilities but also support the broader objective of creating a more sustainable future for global maritime transport[74].

1.2.19. The Cyclical Nature of Shipping Markets

The inherently cyclical nature of shipping markets plays a critical role in shaping decision-making and strategic planning within the maritime sector. Martin Stopford's comprehensive analysis in *Shipping Market Cycles*[75] offers an in-depth exploration of how these cycles function, emphasizing the dynamics between supply and demand, the influence of global economic trends, and the strategic implications for shipping companies.

Shipping markets typically experience recurring periods of expansion and contraction, driven by fluctuations in cargo demand and shipping capacity. These cycles can be divided into four main phases: expansion, peak, contraction, and trough.

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[72] Rodrigue, J.-P., Notteboom, T., & Pallis, A. A. (2020). *Chapter 3.2 – The Digital Transformation of Ports*. In *Port Economics, Management and Policy*.
[73] World Bank. (2023, January 6). *How a digital platform for ports speeds delivery of goods to your local shopping mall*.
[74] MDPI. (2022). *Innovation in Smart Ports: Future Directions of Digitalization and Sustainability*. *Journal of Marine Science and Engineering*, 10(12), 1925
[75] Stropford, M. (2010) 'Shipping Market Cycles', in *The Handbook of Maritime Economics and Business*.

The expansion phase occurs when the demand for maritime transport begins to outstrip the supply of vessels. Stimulated by global economic growth, rising cargo volumes push freight rates upward, resulting in higher profitability for shipping companies. In response to these favourable market conditions, shipowners often invest heavily in newbuild orders, seeking to maximize returns by increasing fleet capacity. The peak phase is characterized by maximum market utilization and elevated freight rates, reflecting a tight balance between supply and demand. However, this stage tends to be short-lived; the surge in shipbuilding triggered during the expansion eventually leads to an oversupply of vessels, setting the stage for a downturn.

During the contraction phase, the influx of new ships into the market creates excess capacity, depressing freight rates and eroding profitability. Shipowners typically respond by slowing new orders and accelerating the scrapping of older, less efficient vessels as a means of restoring balance to the market.

The trough phase represents the bottom of the cycle. Here, freight rates are at their lowest, and the market struggles with surplus shipping capacity. In this environment, shipping companies focus on cost containment, operational efficiency, and asset management strategies to survive the downturn. Gradually, as inefficient vessels exit the market and demand begins to recover, the cycle transitions once again toward expansion. These cyclical patterns are shaped by a range of external factors, including the state of the global economy, shifts in trade policies, technological developments, and geopolitical events. Each of these influences can alter both the demand for maritime services and the operational costs associated with shipping, further affecting the market cycle's progression. Successfully navigating the volatility of shipping markets requires strategic foresight and adaptability. Shipping companies must base investment decisions on careful analysis of market trends, economic indicators, and the specific dynamics of various market segments, such as tankers, bulk carriers, and container ships. Operational flexibility and financial resilience are essential qualities, enabling firms to adapt swiftly to market fluctuations, mitigate risks during downturns, and seize opportunities during periods of growth.

In conclusion, while the cyclical nature of shipping markets presents significant challenges, it also offers opportunities for well-prepared maritime businesses. Through strategic fleet management, informed investment planning, and operational agility, shipping companies can effectively navigate these cycles, ensuring long-term sustainability and profitability.

1.3. Green Corridors

The concept of green shipping corridors has rapidly gained traction as a key strategy for advancing the decarbonization of the maritime sector. As outlined in the article published by *Bunkerspot* (2023), green corridors refer to specific maritime routes between two or more ports where zero-emission shipping solutions are deployed and supported by appropriate infrastructure. The idea received strong momentum with the Clydebank Declaration at COP26[76], where 24 nations committed to promoting these sustainable routes. In some ways, the modern notion of green corridors echoes historical navigation practices, when seafarers relied on favourable environmental conditions such as winds and currents to plan their voyages. Today, the concept integrates technological innovation, renewable energy sources, and international political cooperation to establish low-impact maritime transport systems. Initial efforts have largely focused on introducing low- and zero-emission fuels, including hydrogen, ammonia, biofuels, and electrification of port and ship operations. However, the paper emphasizes that the potential of wind propulsion technologies has been significantly underestimated. Wind energy, being abundant and free, represents a highly promising resource. According to the International Windship Association (IWSA)[77], adopting wind-assist systems and designing vessels optimized for primary wind propulsion could dramatically reduce fuel consumption, lower operational costs, and accelerate the transition towards genuinely sustainable shipping practices. Currently, more than 24 large commercial vessels are equipped with wind propulsion systems, with many other projects under development. The integration of wind energy into green corridors could not only minimize environmental impact but also reduce the economic risks associated with dependence on alternative fuel infrastructures that are still in the early stages of development. The paper also highlights several challenges facing the implementation of green corridors, such as the risk of technological and infrastructural lock-in, the possibility of exacerbating social and economic inequalities at the expense of smaller ports or ports located in developing countries, and the necessity of considering broader environmental impacts beyond CO_2 emissions, including black carbon, volatile organic compounds (VOCs), and underwater noise pollution. An energy-centred approach that combines wind propulsion with alternative fuels is presented as a more resilient solution, capable of reopening commercially marginal routes, enhancing the resilience of maritime supply chains, and making the sector less vulnerable to energy market volatility. Furthermore, the widespread adoption of wind technologies could significantly reduce costs, with estimated savings of approximately 10% for each doubling of installed systems[78]. In conclusion, while green shipping corridors offer immense potential for driving the maritime energy transition, their success will depend on the ability to

[76] UK Government. (2021, November 10). *Clydebank Declaration for green shipping corridors*. UN Climate Change Conference UK 2021.
[77] International Windship Association. (2024). *White paper on wind propulsion: Submitted to MEPC81 by Comoros, France, Solomon Islands and IWSA*. International Maritime Organization (MEPC 81/INF.39).
[78] Akhavan, M. (2025). Decarbonising maritime transport: The role of green shipping corridors in making sustainable port-city ecosystems. *Ocean and Society, 2*, Article 9411.

integrate diverse technologies, to plan inclusively, and to carefully consider global social and economic implications. Maritime history demonstrates that intelligently harnessing natural forces, in combination with modern technological innovation, may be the key to building a truly sustainable future for global shipping.

1.4. The Regulatory Landscape

The maritime industry plays a fundamental role in global trade, but its environmental impact has led to an increasingly stringent regulatory framework. Governments and international organizations are adopting progressive measures to reduce emissions and improve sustainability, with the International Maritime Organization (IMO) at the forefront of these efforts. As the specialized United Nations agency overseeing maritime regulations, the IMO has introduced key treaties and standards aimed at limiting pollution and enhancing energy efficiency across the sector.

One of the most significant regulatory milestones is the MARPOL[79] Convention (International Convention for the Prevention of Pollution from Ships), originally adopted in 1973 and reinforced with the 1978 Protocol, forming what is now known as MARPOL 73/78. This treaty remains a cornerstone of environmental protection in maritime transport, setting limits on various pollutants released by ships, including oil, chemicals, sewage, and garbage. Building upon MARPOL, the IMO 2020 regulation[80] marked a major shift by reducing the sulfur content in marine fuels from 3.5% to 0.5%, significantly cutting sulfur oxide (SOx) emissions and improving air quality worldwide. More recently, IMO's 2023 Strategy set even more ambitious targets, aiming for a 100% reduction in greenhouse gas (GHG) emissions by 2050. These objectives have prompted the development of specific tools to assess and improve ship efficiency.

To regulate energy performance, the IMO has introduced, from 1 January 2023, the Energy Efficiency Existing Ship Index (EEXI)[81], which makes mandatory evaluate the environmental performance of ships above 5,000 gross tonnages (GT), and the Energy Efficiency Design Index (EEDI)[82], which sets efficiency requirements for newly built vessels. In parallel, the Ship Energy Efficiency Management Plan (SEEMP Part III)[83] and the Carbon Intensity Indicator (CII)[84] enable shipowners to monitor and

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[79] International Maritime Organization (IMO), *International Convention for the Prevention of Pollution from Ships (MARPOL)*, 1973 as modified by the Protocol of 1978.
[80] https://www.imo.org/en/MediaCentre/PressBriefings/pages/34-IMO-2020-sulphur-limit-.aspx
[81] https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx
[82] https://www.imo.org/fr/MediaCentre/HotTopics/Pages/EEDI.aspx
[83] Marine Environment Protection Committee. (2022). *Resolution MEPC.346(78): 2022 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP)*. International Maritime Organization.
[84] https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/

progressively improve their CO_2 emissions performance, with increasingly stringent requirements over time[85].

1.4.1. European Regulations: A More Stringent Framework

While IMO regulations set global standards, the European Union (EU) has developed an even stricter regulatory framework to align with the European Green Deal[86] and the Fit for 55 package[87], aiming for full decarbonization of the maritime sector. From 2024, shipping has been included in the EU Emissions Trading System (ETS)[88], requiring vessels above 5,000 GT to purchase carbon allowances for 100% of emissions in European waters and 50% of emissions related to voyages to and from EU ports. This inclusion follows the EU Regulation 2015/757 (MRV Regulation)[89], which mandates companies to monitor, report, and verify CO_2 emissions within the European Economic Area (EEA). The transition is gradual, with the required carbon allowances increasing from 40% in 2024 to 100% by 2026.

A complementary regulation, FuelEU Maritime[90], which entered into force on January 1st 2025, will impose progressively stricter limits on the greenhouse gas intensity of maritime fuels. The regulation incentivizes the adoption of alternative fuels such as biofuels, hydrogen, and green ammonia, driving innovation in propulsion technologies and energy storage solutions. In addition to carbon pricing and fuel regulations, the EU has also established Emission Control Areas (ECAs)[91] in the Baltic Sea, North Sea, and English Channel, where the maximum sulfur content in marine fuels is capped at 0.10%, a significantly lower threshold than the 0.50% limit imposed globally by the IMO. These stricter regional controls highlight Europe's proactive stance in mitigating the environmental impact of shipping.

From 2026, another major policy instrument, the Carbon Border Adjustment Mechanism (CBAM)[92], will introduce a carbon pricing system for imported goods with high CO_2 footprints, directly affecting the maritime industry by increasing costs for emissions-intensive cargo entering the EU. This mechanism represents one of the European Union's key regulatory innovations aimed at addressing

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[85] Bach, H., & Hansen, T. (2023). IMO off course for decarbonisation of shipping? Three challenges for stricter policy. *Marine Policy, 147*, 105379

[86] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_it

[87] Soone, J. (2023). *Sustainable maritime fuels: 'Fit for 55' package – The FuelEU Maritime proposal*. European Parliamentary Research Service.

[88] https://www.dnv.com/maritime/insights/topics/eu-emissions-trading-system/

[89] European Commission, Directorate-General for Climate Action. (2024). *The EU ETS and MRV Maritime: General guidance for shipping companies* (Guidance document No. 1, Updated Version, 5 November 2024).

[90] https://www.dnv.com/maritime/insights/topics/fueleu-maritime/

[91]https://www.imo.org/en/OurWork/Environment/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx

[92] https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

the challenge of decarbonisation in a globalised economic context. Introduced as part of the Fit for 55 package, the CBAM seeks to prevent the phenomenon of carbon leakage–that is, the relocation of European companies to countries with less stringent climate regulations–while ensuring a level playing field for EU producers. Initially applying to carbon-intensive sectors such as cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen, the CBAM requires importers to purchase CBAM certificates corresponding to the embedded greenhouse gas emissions in imported goods. In this way, the CBAM rebalances the carbon cost between domestic and imported products, reducing the risk that the EU's decarbonisation efforts are offset by an increase in the carbon footprint of imports. The implementation of the CBAM is structured in two phases: a transitional phase (October 2023 to December 2025), during which importers are required only to collect and report data on embedded emissions, and a definitive phase (beginning 1 January 2026), when the obligation to purchase CBAM certificates will come into effect. In February 2025, the European Commission proposed a new legislative measure known as the Omnibus Regulation, aimed at simplifying the CBAM. The regulation is part of the broader technical and operational review of the Green Deal's regulatory framework and introduces targeted adjustments to the CBAM in preparation for its full application. If approved by the European Parliament and Council, the Omnibus Regulation will introduce several key changes: the gradual phase-out of free ETS allowances for sectors covered by the CBAM, to avoid double protection and encourage real emissions reductions; the introduction of a de minimis threshold of 50 tonnes of CO_2 equivalent per importer per year, below which CBAM obligations will no longer apply, thereby easing the administrative burden on small businesses, but still ensuring coverage, according to the Commission, of 99% of the emissions; the extension of the annual CBAM reporting deadline from 31 May to 31 August; enhanced methodological alignment between CBAM and the EU ETS emission calculation standards; and strengthened anti-evasion measures through more rigorous monitoring and closer cooperation between customs and climate authorities.

1.5. Technology solutions

Achieving net-zero emissions in the maritime sector requires a profound technological and operational transformation, supported by substantial capital investments. To meet international emissions reduction targets, the industry must adopt cutting-edge technologies and fundamentally reshape its operational models. Some innovative solutions, such as carbon capture and storage (CCS) systems, remain partially outside the direct control of shipping companies. In the meantime, significant improvements can be achieved by implementing energy efficiency technologies and optimized operational practices, promoting a transition towards cleaner and more sustainable methods of navigation. A central element of this strategy involves shifting to low-carbon fuels and improving fuel efficiency across entire fleets. Deploying highly efficient technologies and adopting advanced management practices allow for a significant reduction in both fuel consumption and overall emissions. The use of alternative fuels, such as liquefied natural gas (LNG), biofuels, and hydrogen, represents a particularly promising and eco-friendly option for powering ships. However, the global expansion of these fuels presents certain challenges, notably the need to develop efficient supply chains and adequate bunkering infrastructure, which can take significant time to establish across different markets[93]. Additionally, some vessel categories, particularly large oceangoing ships, may still require the use of conventional fuels for specific operational needs. To address these issues, the industry should focus on promoting the use of alternative fuels in segments where their adoption is most immediately viable and impactful, such as short-sea shipping and coastal operations. While the transition from fossil fuels to low-carbon energy sources can provide limited short-term emissions mitigation, current practices and policies suggest that a substantial share of maritime transport will continue to rely on conventional fuels for the foreseeable future[94]. Consequently, the sector' s full decarbonisation will ultimately depend on the widespread adoption of breakthrough technologies, such as electric propulsion systems and fuel cells. According to the International Maritime Organization (IMO), deploying carbon capture and storage technologies, hydrogen-based propulsion systems, and material efficiency strategies could drastically reduce the sector's CO_2 emissions while curbing demand growth. However, maximizing the potential of energy-efficient technologies requires the implementation of rigorous design and operational policies, centered on the reusability of ship components, material recycling, and the prevention of contamination, thus facilitating sorting, disassembly, and material recovery processes. In this context, the adoption of Best Available Techniques (BAT) plays a pivotal role. BAT refers to the most effective and advanced technological and operational solutions currently available to minimise the environmental impact of maritime activities[95]. In shipping, BAT includes practices such as hydrodynamic hull optimization, the use of high-efficiency or alternative-fuel engines, the installation of emissions abatement systems (such as scrubbers and catalytic converters), and the integration of advanced onboard energy management systems. Incorporating BAT into fleet renewal and operational strategies not only enables a significant

[93] https://maritime-zone.com/en/news/view/how-new-maritime-technologies-will-change-the-shipping-industry
[94] https://marine-digital.com/article_technologies_in_shipbuilding
[95] Organisation for Economic Co-operation and Development (OECD). (2017). *Best available techniques (BAT) for preventing and controlling industrial pollution: Activity 1: Policies on BAT or similar concepts across the world* (Series on Risk Management, No. 34). OECD Environment, Health and Safety Publications.

reduction in fossil fuel consumption and greenhouse gas emissions but is also essential for maintaining competitiveness within an increasingly sustainability-driven regulatory and financial environment.

1.5.1. Current decarbonization technologies and processes

The maritime industry, in its current trajectory towards decarbonization, relies on a series of already operational technologies whose effectiveness has been validated through both commercial experiences and academic research. Among these, the use of alternative fuels such as liquefied natural gas (LNG), advanced biofuels, and increasingly methanol, constitutes one of the main pathways. LNG allows for a significant reduction in emissions of sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter compared to traditional fuels, serving as a transitional solution. However, the issue of methane slip remains, referring to the release of unburned methane into the atmosphere, a greenhouse gas with a much higher warming potential than CO_2 (Balcombe et al., 2019)[96]. Biofuels derived from biomass and waste materials represent a valid alternative due to their compatibility with existing engines, but raise concerns about the sustainability of the supply chain and large-scale availability, as highlighted in the manual "Alternative Fuel Selection Framework toward Decarbonizing Maritime Deep-Sea Shipping" by Moshiul, Mohammad, and Hira (2023)[97], published in Sustainability, which proposes a decision-making framework for evaluating alternative fuel options based on environmental, technological, and economic criteria.

Beyond fuels, a wide range of energy efficiency technologies is currently available to improve ship performance and reduce environmental footprint. Systems such as air lubrication, optimized hull hydrodynamics, and high-efficiency propellers can achieve fuel consumption reductions between 5% and 10% (DNV GL, 2020)[98]. Additionally, hybrid propulsion systems combining diesel engines with batteries are particularly effective for short-sea shipping contexts, as highlighted in the document "Systematic Overview of Newly Available Technologies in the Green Maritime Sector" by Vidović, Šimunović, Radica, and Penga (2023)[99], published in Energies. This study analyzes hybrid and electric technologies as strategic levers to reduce direct emissions and improve operational flexibility, while also highlighting the current limitations in terms of battery range and capacity. Even though

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[96] Balcombe, P., Anderson, K., Speirs, J., Brandon, N., & Hawkes, A. (2019). Methane emissions from LNG ships: A review of the methods and results. *Energy & Environmental Science*, 12(2), 466–491.
[97] Moshiul, A. M., Mohammad, R., & Hira, F. A. (2023). Alternative fuel selection framework toward decarbonizing maritime deep-sea shipping. *Sustainability*, *15*(6), 5571.
[98] DNV. (2023). *Maritime Forecast to 2050*. Det Norske Veritas.
[99] Vidović, D., Šimunović, N., Radica, G., & Penga, N. (2023). Systematic overview of newly available technologies in the green maritime sector. *Energies*, *16*(3), 1225.

some of these technologies are still undergoing refinements, their commercial availability already exists.

Wind-assisted propulsion is experiencing renewed interest, with solutions such as Flettner rotors, rigid sails, and traction kites. The "White Paper on Wind Propulsion," submitted to the IMO by Comoros, France, Solomon Islands, and the International Windship Association (IWSA-2024)[100], analyzes the potential of wind propulsion to reduce fossil fuel consumption and improve energy efficiency, while acknowledging the need to overcome regulatory and operational barriers. According to Hoffmeister et al. (2025), in their study "Wind-Assisted Propulsion Systems (WAPS): How WAPS Can Help to Comply with GHG Regulations," WAPS technologies can contribute up to a 20% reduction in fuel consumption on favourable ocean routes[101].

Digitalization also plays a central role in decarbonization strategies, through real-time monitoring, predictive maintenance, and optimized energy management. The adoption of advanced route optimization tools and computational simulations enables an overall improvement in ship operational efficiency. In parallel, the use of innovative materials and optimized hull designs, as discussed in the HIPER'23 – 15th Symposium on High-Performance Marine Vehicles[102], contributes to reducing hydrodynamic resistance, enhancing sustainability, and lowering operational costs. Advanced antifouling coatings and air lubrication technologies are examples of already adopted solutions to increase hull smoothness and reduce energy consumption.

1.5.2. Emerging Technologies in the Maritime Sector

Alongside established solutions, the maritime industry is exploring a new generation of emerging technologies that promise a radical transformation of the sector. At the forefront is the development and adoption of fully carbon-free fuels such as ammonia, hydrogen, and synthetic methanol. The manual "A Prompt Decarbonization Pathway for Shipping: Green Hydrogen, Ammonia, and Methanol Production and Utilization in Marine Engines" by Shi, Zhu, Feng, Yang, and Xia (2023)[103], published in Atmosphere, provides a comprehensive overview of the production methods and applications of these fuels in marine engines, highlighting their potential in achieving net-zero

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[100] Comoros, France, Solomon Islands, & International Windship Association. (2024, January). *White paper on wind propulsion*. Submission to the Marine Environment Protection Committee, 81st session, Agenda item 7 (MEPC 81/INF.39). International Maritime Organization.

[101] Hoffmeister, H., Hollenbach, U., Tranell, J., Aalbu, K., Skåre, O. G., Endresen, Ø., Stefanatos, J., Kvålsvold, J., Hustad, H., Longva, T., Wienke, J., Leisner, M., & Schäfer, J. (2025). *How wind-assisted propulsion systems (WAPS) can help to comply with GHG regulations*. DNV.

[102] Bertram, V. (Ed.). (2023). *Proceedings of the 15th Symposium on High-Performance Marine Vehicles (HIPER'23)*, Bernried, 18-20 September 2023. DNV Maritime.

[103] Shi, J., Zhu, Y., Feng, Y., Yang, J., & Xia, C. (2023). A prompt decarbonization pathway for shipping: Green hydrogen, ammonia, and methanol production and utilization in marine engines. *Atmosphere, 14*(3), 584.

emission targets. Hydrogen, particularly green hydrogen, stands out for its zero environmental impact during combustion, but presents significant challenges in terms of storage, transportation, and infrastructure requirements. Ammonia, while carbon-free, is a toxic substance that requires stringent safety standards, whereas methanol, if produced from renewable sources, represents a good compromise between energy density, safety, and infrastructure compatibility[104]. The report Environmental Impacts of Ammonia Spills in Marine Environments by Ricardo and the Maritime Decarbonization Hub (2022)[105] emphasizes the significant environmental and safety risks associated with the use of ammonia as a marine fuel. The paper highlights the high toxicity of ammonia to marine ecosystems, the rapid formation of hazardous clouds in the event of a spill, and the potential for long-term ecological damage due to its persistence in the aquatic environment. The study therefore underscores the urgency of developing appropriate safety protocols, effective spill response strategies, and a robust regulatory framework to manage the risks associated with future large-scale adoption of ammonia in shipping. The integration of these new fuels is closely linked to the adoption of alternative propulsion systems. Fuel cells, particularly PEMFC and SOFC, offer high-efficiency energy conversion with low local emissions. However, they are still limited by high implementation costs and the need to improve system durability and thermal management (Douvartzides et al., 2021)[106]. Even the paper *Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives* by Elkafas, Rivarolo, Gadducci, Magistri, and Massardo (2023)[107], published in *Processes*, provides an in-depth overview of the use of fuel cell technologies in the maritime sector, with a particular focus on PEMFC (Proton Exchange Membrane Fuel Cells) and SOFC (Solid Oxide Fuel Cells). The study examines their technological development, current applications, available commercial products, and prospects. PEMFCs, operating at low temperatures, are characterized by high power density and fast start-up times, making them suitable for high-speed vessels and ferries, although they require pure hydrogen and are sensitive to fuel impurities. SOFCs, on the other hand, operate at high temperatures, offer greater energy efficiency, and can utilize a broader range of fuels such as methanol, ammonia, and LNG, which makes them ideal for large cruise and cargo ships despite their slower start-up and more complex thermal management. The paper discusses real-world applications and demonstration projects led by

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[104] Ricardo. (2024). *Ammonia environmental impact study*. Ricardo Energy & Environment

[105] Ricardo PLC, & Maritime Decarbonization Hub. (2022). *Environmental impacts of ammonia spills in marine environments*. Ricardo PLC

[106] Douvartzides, S. L., Charisiou, N. D., Katsimbras, D., & Doukelis, A. (2021). A review on hydrogen carriers for marine applications: Ammonia, methanol and liquid organic hydrogen carriers. *Journal of Power Sources*, 490, 229484

[107] Elkafas, A. G., Rivarolo, M., Gadducci, E., Magistri, L., & Massardo, A. F. (2023). Fuel cell systems for maritime: A review of research development, commercial products, applications, and perspectives. *Processes, 11*(1), 97.

companies like Ballard Power Systems and Bloom Energy, and highlights major barriers to large-scale adoption, including high capital costs, limited refuelling infrastructure, and the absence of clear regulatory standards from the IMO. Despite these challenges, the study emphasizes that fuel cells represent one of the most promising solutions for maritime decarbonization, especially when integrated with renewable energy and digital technologies, and calls for policy support and targeted investments to accelerate their deployment.

Fully electric vessels, powered exclusively by batteries, are growing in short-sea routes, but the low energy density of current batteries limits their application on large-scale oceanic voyages. Solar energy and wave energy converters are also being explored as auxiliary sources, although their contribution remains marginal compared to the total energy needs of ocean-going vessels.

In the field of mechanical propulsion, the HIPER'23 document[108] highlights the evolution of hull designs toward more vertical shapes without bulbous bows, optimized for lower operational speeds. The use of lightweight and advanced composite materials, such as aluminium alloys and metal foams, reduces structural weight and improves fuel efficiency. Advanced silicon-based antifouling coatings and in-water robotic hull cleaning technologies complete the suite of technical solutions aiming to reduce drag and improve the durability of ship surfaces. Finally, the increasing use of digital twins, CFD simulations, and automation systems is enabling a new phase of intelligent ship design and management, where efficiency and sustainability are integrated from the concept stage.

The future of maritime transport will depend on the sector's ability to integrate these emerging technologies into a coherent ecosystem, supported by adequate infrastructure, favourable regulations, and financing mechanisms oriented towards sustainability. Only through a systemic and collaborative approach will it be possible to ensure an effective and inclusive transition toward zero-emission maritime transport[109].

Existing Technologies	**Emerging Technologies**
LNG, biofuels	Ammonia, hydrogen as primary fuels
Scrubbers, waste heat recovery systems	Onboard carbon capture (CCS)
Wind-assisted propulsion	Advanced fuel cells
Hybrid and battery-powered ships (short range)	Full-electric ships for longer routes
Route optimization (AI and Big Data)	Digital twins, autonomous shipping
Auxiliary solar panels	Wave energy converters
Operational efficiency measures	Advanced lightweight materials

Table 1 *– Comparative summary of existing and emerging technologies in the shipping sector*

[108] Bertram, V. (Ed.). (2023). *Proceedings of the 15th Symposium on High-Performance Marine Vehicles (HIPER'23)*, Bernried, 18-20 September 2023. DNV Maritime.

[109] ABS. (2022–2023). *Reports on Digitalization and Renewables*. American Bureau of Shipping.

1.6. Introduction to Transition Risks in the Maritime Sector

The transition toward a low-carbon economy has placed the maritime sector at the center of a complex and multi-dimensional risk landscape. These risks, known as transition risks, go far beyond issues of regulatory compliance or technological innovation. They directly affect the profitability, operational resilience, and financial viability of shipping companies, and can transmit systemic exposure to financial institutions and insurers. Arising from intensifying regulatory, financial, technological, and reputational pressures, transition risks constitute a critical challenge for an industry undergoing structural transformation.

Chapter 2 will explore the core dimensions of these transition risks, organizing the analysis into six distinct yet interrelated categories:

1. Regulatory and policy risks, stemming from increasingly stringent environmental measures (e.g., EU ETS, FuelEU Maritime, CII, EEXI) and the fragmented international regulatory landscape;
2. Technological risks, related to uncertainty around alternative fuels, the risk of technological lock-in, and the limited maturity of many decarbonization technologies;
3. Economic and financial risks, driven by rising operational costs, high capital intensity, and the growing selectivity of ESG-driven financial institutions;
4. Market and reputational risks, reflecting shifting customer preferences, stakeholder scrutiny, and the expanding importance of climate transparency and ESG credibility;
5. Asset obsolescence risks, concerning the accelerated devaluation of high-emission vessels and the strategic implications for asset longevity and collateral value;
6. Infrastructure-related systemic risks, associated with the lack of adequate port facilities and global asymmetries that constrain the scalable deployment of zero-emission fleets.

By examining each of these dimensions, the chapter aims to provide a comprehensive and integrated understanding of the vulnerability factors that shape the long-term sustainability and bankability of the maritime decarbonization process. These risks should not be interpreted merely as short-term hurdles, but as structural determinants of competitiveness in an industry increasingly shaped by climate alignment. As such, they must be actively incorporated into industrial planning, cash flow modeling, and the capital allocation frameworks of banks, investors, and regulators.

1.7. Transmission Channels

In the context of the shift towards a low-carbon economy, transmission channels are the mechanisms through which climate-related, regulatory, technological, and market transformations propagate economic and financial effects from their origins to various actors within the system, particularly businesses, investors, financial institutions, and public administrations. Simply put, they represent the pathways through which changes such as the introduction of a carbon tax, the banning of a fossil fuel, or a disruptive technological innovation spread throughout the economic system, altering asset values, corporate profitability, consumer behaviours, and investment decisions[110].

Understanding these channels is essential for anticipating the systemic impacts of ecological transition and for implementing effective mitigation strategies at both corporate and macroeconomic levels. Functionally, transmission channels link climate risk dynamics to traditional forms of financial risk (credit, market, liquidity, operational), enabling financial institutions and supervisory bodies to integrate climate risks into assessment models, stress testing, and risk management frameworks[111]. In other words, they serve as analytical bridges that make the impacts of transition risks on economic and financial stability visible and measurable. They are also central to evaluating the exposure of financial intermediaries, planning effective public policies, and directing capital flows towards resilient and sustainable assets.

The main types of transmission channels can be categorized into three macro-groups[112]: microeconomic, macroeconomic, and financial. Microeconomic channels refer to the direct impact of transition risks on individual economic operators, such as businesses and households. For instance, a carbon-intensive company may face additional costs due to new environmental taxes or mandatory technological retrofits, leading to reduced profitability, loss of competitiveness, and potential deterioration of creditworthiness. Similarly, households exposed to energy shocks or sectoral employment transitions may decrease consumption or struggle to repay mortgages. Macroeconomic channels, on the other hand, concern the aggregate effect of these risks on the economy as a whole. A disorderly transition can negatively influence GDP, employment, inflation, and aggregate demand, generating widespread instability and uncertainty. Financial channels represent the mechanisms through which transition risks affect asset valuations, counterparty solvency, market liquidity, and the stability of the financial system. For example, the depreciation of "brown" assets (i.e., those with high

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[110] Basel Committee on Banking Supervision. (2021). *Climate-related risk drivers and their transmission channels*. Bank for International Settlements

[111] Management Solutions. (2021). *Climate-related risk: drivers, transmission channels and implications for the banking sector*.

[112] Bank for International Settlements. (2023). *Climate Risks in Banking – Transmission Channels*.

carbon intensity) can lead to losses for investors and banks, trigger liquidity runs or cause sudden shifts in portfolios. This type of transmission is particularly relevant for the insurance and banking sectors, which hold significant exposures in climate-risk-prone sectors.

In summary, transition risk transmission channels play a crucial role in analyzing the economic sustainability of climate change, as they explain how and why a climatic or political event can transform into a tangible economic and financial risk. Understanding them is now an indispensable requirement for effective governance of ecological transition, the resilience of financial systems, and the development of informed corporate strategies capable of anticipating changes rather than merely reacting to them.

1.8. Transition Plans in the Shipping Sector: International Standards and Operational Guidelines (ACT, TPT, EFRAG)

Transition plans in the shipping sector are key to guiding shipping companies toward decarbonization while ensuring regulatory compliance, market competitiveness, and access to capital. Three key initiatives offer structured guidelines for developing credible and transparent plans: the Assessing Low Carbon Transition (ACT) Initiative, the UK's Transition Plan Taskforce (TPT), and EFRAG's Implementation Guidelines under the Corporate Sustainability Reporting Directive (CSRD).

1.8.1. ACT (Assessing Low-Carbon Transition)

In the context of increasing global attention to the decarbonization of the real economy, the ACT Framework (Assessing Low-Carbon Transition)[113] represents one of the most comprehensive tools for evaluating the consistency and effectiveness of corporate strategies aimed at transitioning towards a low-greenhouse gas (GHG) emissions economy. Launched in 2015 by ADEME and CDP and currently led by the World Benchmarking Alliance (WBA), the ACT Initiative provides a standardized methodology to transparently assess the alignment of companies with the climate goals of the Paris Agreement, particularly with pathways limiting global warming to 1.5°C or “well below 2°C” (ACT, 2024).

The Version 2.0 of the framework, released in November 2024, adopts a systemic and multidimensional approach that integrates both quantitative indicators (e.g., direct and indirect emissions, R&D investments, product-level emission intensity) and qualitative metrics (e.g., strategic coherence, climate governance, stakeholder engagement, reputation, and risk management). The

[113] World Benchmarking Alliance, & ADEME. (2024). *ACT Framework – Assessing the transition towards low GHG emissions (Version 2.0)*. ACT Initiative.

assessment structure consists of three core components: a performance score (ranging from 0 to 20), a narrative score (from A to E), and a trend score (+, =, -), with the aim of delivering both a snapshot and a forward-looking perspective of a company's low-carbon transition.

A key feature of the ACT Framework is its modular architecture, which includes nine thematic modules covering the entire corporate activity chain, from strategy-setting (emissions targets, business model transformation) to operational execution (capital investments, product decarbonization, policy engagement). This structure allows for sector-specific adaptations while maintaining comparability through the ACT Generic Methodology, developed to assess companies not covered by specific sectoral frameworks. The framework is grounded in five core assessment principles—relevance, verifiability, ambition, conservativeness, and consistency—which guide data selection, methodological rigor, and evaluator judgment. Special emphasis is placed on integrating Scope 1, 2, and 3 emissions, aligning with recognized climate scenarios (e.g., SBTi, IPCC), and assessing key indicators such as "locked-in emissions" and corporate carbon budgets.

A notable innovation introduced in Version 2.0 is the explicit consideration of enabling activities—economic operations that, while not directly low-carbon, are critical to supporting the decarbonization of other actors (e.g., renewable energy technologies, low-emission transport infrastructure). The framework proposes a tailored scoring approach for such entities, recognizing their strategic role without penalizing them for short-term increases in absolute emissions. Lastly, the document outlines the development of a new scalable methodology: ACT Core. This tool is designed to assess the credibility of corporate transition plans across large datasets, facilitating portfolio-level analysis by financial institutions. It aims to balance simplicity and sectoral sensitivity, leveraging core ACT principles while adapting to the fragmented nature of public climate disclosures.

In summary, the ACT Framework serves not only as an evaluative tool but also as a strategic lever to enhance corporate climate accountability. It represents a key methodological reference for assessing climate-related performance and transition readiness within the private sector.

1.8.2. TPT (Transition Plan Taskforce)

The Transition Plan Taskforce (TPT), established by the UK government during COP26 in 2021, has played a pivotal role in shaping international standards for credible and robust climate transition plans. Its *Final Report* (TPT, 2024)[114] offers a comprehensive review of the progress achieved over its mandate and outlines future directions for embedding transition plans in corporate and financial

[114] Transition Plan Taskforce. (2024). *Progress achieved and the path ahead: The final report of the Transition Plan Taskforce*. HM Treasury.

practices globally. The TPT's core contribution lies in the development of a "gold standard" Disclosure Framework, which is sector-neutral and intended to support companies and financial institutions in formulating and reporting transition plans aligned with the Paris Agreement's 1.5°C goal. The framework is structured around three guiding principles—Ambition, Action, and Accountability—and encompasses five key elements: strategic foundations, implementation strategy, engagement, metrics and targets, and governance. Since its launch, the TPT has catalysed widespread adoption of transition planning across sectors. According to CDP (2024), more than 5,900 companies reported having a 1.5°C-aligned transition plan in 2023, a 44% increase from the previous year. Furthermore, a growing number of financial institutions are integrating transition plans into their risk assessment, capital allocation, and engagement strategies (OECD, 2022; TFMR, 2024). As the report highlights, credible transition plans are becoming essential for accessing transition finance and for aligning corporate trajectories with national and international climate policy objectives.

A key milestone in the mainstreaming of the TPT's work was the transfer of its disclosure materials to the IFRS Foundation in June 2024, ensuring alignment with IFRS S2 standards and enhancing global consistency in climate-related disclosures. This institutional integration is expected to reduce regulatory fragmentation and strengthen the reliability of reported transition data.

The report also emphasises the importance of transition plans as multi-purpose tools, serving strategic change management within companies, enabling informed investment decisions, and guiding policymaking. Evidence suggests that companies with credible plans benefit from lower financing costs and enhanced competitiveness (Zhou et al., 2024; Lloyds Bank, 2024). On the regulatory side, the UK, EU, and G7 have all endorsed the use of transition plans as a lever for systemic decarbonisation, while jurisdictions like Australia, Brazil, China, Malaysia, and the US are implementing complementary frameworks.

Looking forward, the TPT identifies four priorities for continuing the global momentum:

1. Strengthening market capabilities and sharing best practices.
2. Developing enabling tools and assurance infrastructure.
3. Integrating transition plans into business and financial decision-making.
4. Promoting global harmonisation of norms and expectations.

Overall, the TPT Final Report positions transition plans as a cornerstone of the low-carbon transition, not only as a reporting obligation but as a strategic mechanism to realign capital, reshape corporate governance, and operationalise sustainability at scale. Its contribution is highly relevant for researchers and practitioners exploring the intersection of corporate climate action, financial regulation, and sustainable development.

1.8.3. EFRAG (European Financial Reporting Advisory Group)

The *Transition Plan Implementation Guidance*[115], published by EFRAG in 2024, is a key technical reference for implementing the disclosure requirements of the European Sustainability Reporting Standards (ESRS), specifically in relation to transition plans for climate change mitigation. These guidelines fall within the framework of the Corporate Sustainability Reporting Directive (CSRD) and are designed to help European companies develop transparent, measurable strategies aligned with the objective of achieving climate neutrality by 2050.

The guidance focuses on ESRS E1-1, which defines the disclosure obligations related to climate mitigation transition plans. According to EFRAG, such a plan must include a structured combination of targets, actions, allocated resources, and business model changes, demonstrating alignment with the Paris Agreement (1.5°C limit) and EU climate policy. Rather than a generic climate strategy, it is a dynamic, auditable instrument that must be fully integrated into the company's governance and business strategy. The framework outlined by EFRAG is structured around several key components:

- the compatibility of GHG emissions reduction targets (Scopes 1, 2, and 3) with science-based pathways;
- the description of "decarbonisation levers", i.e., strategic actions and technologies to achieve those targets;
- the quantification of investments and funding (CapEx/OpEx) related to the plan;
- the evaluation of "locked-in emissions", emissions that are structurally embedded in long-lived assets;
- the integration of the transition plan into corporate strategy, with explicit oversight from governance bodies;
- the reporting on progress made toward the implementation of planned milestones.

A crucial aspect of the document is its cross-referencing across ESRS standards: disclosure requirements on strategy (SBM), governance (GOV), material impacts and risks (IRO), policies, and targets (MDR) all contribute to ensuring the consistency and credibility of the transition plan. Moreover, the guidance highlights the importance of disclosing the social and environmental impacts of transition-related actions (e.g., Just Transition, biodiversity, resilience), promoting an integrated view of sustainability. EFRAG adopts a modular and flexible approach, proposing implementation options and tools such as the *CTP Workbook* to support data collection and reporting. While non-binding, the guidance serves as a highly authoritative technical aid for companies subject

[115] EFRAG. (2024). *Transition plan for climate change mitigation: Implementation guidance*

to CSRD requirements and for stakeholders assessing the quality and credibility of corporate transition strategies.

In summary, the EFRAG guidance contributes to the standardization and strengthening of climate-related disclosures in the EU, offering a clear operational framework to embed ecological transition into strategic corporate planning.

Chapter 2: The Role of Banks in the Maritime Transition and Climate Risk Analysis

2.1. Introduction to bank's approach to decarbonisation: objectives and constraints

In recent years, the banking sector has taken an increasingly central role in driving the transition to a low-carbon economy, acting as a strategic lever to steer capital flows towards activities that are compatible with international climate goals. In the context of the maritime transition, this function is particularly relevant, as the shipping sector is historically responsible for about 3% of global greenhouse gas emissions (IMO, 2020),[116] but at the same time represents a critical infrastructure for international trade. Banks, as the main financiers of merchant fleets, are therefore called upon to assess the risks and opportunities related to climate change in their credit portfolios in an increasingly integrated way.

In this context, the global financial system plays a crucial role in determining the pace and direction of the energy transition, influencing both the speed and feasibility of decarbonization. The financial aspect is one of the main obstacles to decarbonization in shipping. The paper "The Real Cost of Decarbonizing in the Shipping Industry" by BCG, in collaboration with the Global Financial Markets Association (GFMA), points out that to achieve full decarbonization of the industry by 2050 will require an operating cost premium of between 10% and 15%, while in the short term this premium could range between 30% and 40%, before alternative fuel production reaches a sufficient level of scale to bring down costs. This highlights an economic competitiveness problem, as most shipping companies operate with relatively low profit margins and are unable to absorb significant cost increases without adequate financial support. The approach of financial institutions has evolved from a traditionally reactive vision, focused on credit and reputational risk management, to a proactive perspective, based on the assessment of the environmental impact of the activities financed. This shift has been driven by several factors: regulatory pressure (e.g., EU Taxonomy, SFDR, CSRD), investor transparency demands (TCFD, 2017),[117] and the emergence of industry standards such as the Poseidon Principles (2023),[118] which offer a voluntary framework to align ship financing with IMO targets on reducing CO_2 emissions by at least 40% by 2030 (compared to 2030 levels). .

[116] IMO (2020). *Fourth IMO GHG Study 2020*. International Maritime Organization.
[117] TCFD (2017). *Recommendations of the Task Force on Climate-related Financial Disclosures*.
[118] Poseidon Principles (2023). *Annual Disclosure Report 2023*.

The objectives of banks in this context are mainly divided into three directions:

1. Strategic alignment with decarbonization trajectories – both for regulatory compliance and for protection of the long-term value of financed assets (NGFS, 2022);[119]
2. Integrated climate risk management – including physical and transition risks in credit assessment models and financial stress tests (ECB, 2022);[120]
3. Development of sustainable financial products – capable of incentivizing virtuous behaviour among shipowners and rewarding the adoption of low-impact technological and operational solutions (ICMA, 2023).[121]

In this regard, the Loan Market Association's "Financing Sustainability in Shipping" paper (2023) focuses on the growing importance of ESG criteria in the maritime sector and emphasizes how investors and customers are becoming increasingly attentive to these parameters, pushing shipping companies to improve their environmental performance to maintain their competitiveness and ensure access to sustainable financing. However, the pursuit of these objectives is subject to several constraints. Firstly, there remains a significant information gap regarding reliable and granular ESG data in the shipping sector, where ownership fragmentation and lack of operational transparency make the assessment of environmental profiles complex (OECD, 2022).[122] Second, climate risk pricing methodologies are not yet fully standardized, making it difficult to integrate them homogeneously into banking decision-making processes (Battiston et al., 2017).[123] Finally, there is a structural tension between time horizons: financing decisions are often tied to short- to medium-term returns, while decarbonisation requires capital-intensive investments with deferred returns over time (UNEP FI, 2021).[124]

Despite these limitations, banks' approach to maritime decarbonization is rapidly maturing, and the idea that financial institutions must not only adapt to the new regulatory and market environment but also play a transformative role in the ecological transition of the real economy is taking root (PRI, 2023).[125]

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[119] NGFS (2022). *Scenarios in Action: A Progress Report on Global Supervisory and Central Bank Climate Scenario Exercises*. Network for Greening the Financial System.
[120] ECB (2022). *Thematic Review on Climate-Related and Environmental Risk*. European Central Bank
[121] ICMA (2023). *Green Bond Principles and Sustainability-Linked Bond Principles*.
[122] OECD (2022). *Decarbonising Maritime Transport: Pathways to zero-carbon shipping by 2050*
[123] Battiston, S. et al. (2017). *A climate stress-test of the financial system*. Nature Climate Change, 7(4), 283–288.
[124] UNEP FI (2021). *Rethinking Impact to Finance the SDGs*.
[125] PRI (2023). *The Role of Banks in the Net Zero Transition*. Principles for Responsible Investment.

2.1.1. Bank commitments to support Net Zero Banking Alliance: A focus on the shipping sector

In the banks' efforts to achieve Net Zero by 2050, the Net-Zero Banking Alliance (NZBA)[126] is the most authoritative framework for defining decarbonisation pathways for credit portfolios, including shipping-related exposures. Participating banks, including BNP Paribas, HSBC and Barclays, are developing specific strategies for the maritime sector to reduce greenhouse gas emissions from their financing activities.

BNP Paribas has defined clear objectives for the decarbonisation of the shipping portfolio in its transition plan. As highlighted in the 2024 Universal Registration Document[127], the bank measures the environmental performance of the portfolio using the Annual Efficiency Ratio (AER) expressed in gCO2e/dwt.nm. In 2023, the emissions intensity of the shipping portfolio was 8.2 gCO2e/dwt.nm, down from 8.3 gCO2e/dwt.nm in 2022, with a 2030 target of 5.6 to 6.4 gCO2e/dwt.nm, in line with the DNV trajectory at 1.6°C[128]. This metric is considered the gold standard by financial institutions to assess the emission efficiency of their shipping portfolios. BNP Paribas has also financed concrete projects such as the $1.1 billion green loan to Hapag-Lloyd for the construction of six new LNG/biogas dual-fuel container ships[129].

HSBC, in its Net Zero Transition Plan (2023),[130] highlights how the shipping sector is among those at highest transition risk, along with oil & gas, steel and aviation. HSBC is committed to supporting customers' transition through financing for innovation, diversification and decarbonisation. The strategy includes intermediate 2030 financed emissions reduction targets and an intensity-based target approach for hard-to-abate sectors such as shipping. HSBC specifies that the financed emissions are measured and reported on an annual basis, with the aim of progressively reducing the climate risk inherent in the portfolio.

Finally, Barclays has included shipping among the 11 key sectors within its Transition Finance Framework 2025[131]. The document identifies activities eligible for transition financing, including the use of low-carbon fuels, the retrofit of existing ships to carry CO2 and the modernisation of port infrastructure for biofuel management. Barclays specifies that: "for the allocation of loans, eligibility criteria are applied based on minimum revenue thresholds (>90%) deriving from activities aligned with transition objectives and provides for the revision of customers'

[126] Net-Zero Banking Alliance. (2021). *Net-Zero Banking Alliance: Commitment Statement*. United Nations Environment Programme Finance Initiative (UNEP FI)
[127] BNP Paribas. (2024). *Universal Registration Document and Annual Financial Report 2024*.
[128] DNV. (2023). *Maritime Forecast to 2050: Energy Transition Outlook*. DNV.
[129] BNP Paribas. (2024). *Universal Registration Document and Annual Financial Report 2024*.
[130] HSBC. (2024). *Our Net Zero Transition Plan*. HSBC Holdings plc.
[131] Barclays. (2025). *Transition Finance Framework Version 1.1*. Barclays Bank plc.

decarbonization plans".[132] Sectoral policies include exclusion or enhanced due diligence for sensitive sectors such as upstream oil & gas and thermal coal, confirming consistency with decarbonisation objectives.

In conclusion, the approach of the three banks highlights the progressive integration of net zero targets into financing strategies, including technical tools for measuring emissions and specific sectoral policies to reduce emissions from the shipping portfolio, in line with the principles of the NZBA.[133] This strategy demonstrates how banks are evolving from a passive lending role to active partners in the global energy transition, supporting the decarbonisation of a critical sector such as maritime.

2.2. Types of Risk (physical, transitional, reputational) and Financial Transmission Channels

In the context of the ecological transition, financial institutions — and banks in particular — are increasingly exposed to new forms of risk arising from climate change and related environmental policies. Such risks can not only undermine the stability of credit portfolios but can also generate systemic effects through different financial transmission channels. The analysis of climate risk is divided, according to the classification now adopted by authorities such as the European Central Bank (ECB, 2022)[134] and the Task Force on Climate-related Financial Disclosures (TCFD, 2017),[135] into three main categories: physical risk, transition risk and reputational risk.

a. *Physical risk*

Physical risks concern the direct and indirect impacts of climate change on the real assets, infrastructures and operational activities of the companies financed. They can be acute, when resulting from extreme events such as cyclones, floods or heat waves, or chronic, when associated with slow but progressive phenomena such as sea level rise, ocean acidification, or changes in sea currents and weather regimes.

In the shipping industry, physical risks manifest themselves along several operational and financial dimensions:

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[132] Barclays. (2025). *Transition Finance Framework Version 1.1*. Barclays Bank plc.

[133] Net-Zero Banking Alliance. (2021). *Net-Zero Banking Alliance: Commitment Statement*. United Nations Environment Programme Finance Initiative (UNEP FI)

[134] European Central Bank. (2022). *Guide on climate-related and environmental risks*.

[135] Task Force on Climate-related Financial Disclosures (TCFD). (2017)

- Damage to ships and port infrastructure caused by extreme events (e.g. tropical storms, storm surges), impacting unplanned CAPEX for repairs and insurance availability.
- Supply chain disruptions due to port closures, changes in trade routes or geopolitical events amplified by climate shocks.
- Re-evaluation of navigation models and decrease in operational efficiency due to deterioration of environmental conditions (e.g. change in currents, changes in sea depth).
- Increase in insurance premiums or, in extreme cases, exclusion of coverage for high-risk geographical areas.

For banks, these elements translate into credit risks (increase in the default rate of affected shipowners), market risks (volatility of cargo and asset values), and operational risks (interruption of logistics or payments). In addition, the increased frequency and intensity of climate events can generate simultaneous losses on multiple assets in the same portfolio, expanding the systemic effect of risk. Numerous reports, including those of the OECD (2022)[136] and the IMO (2020),[137] underline how climate resilience must become a key criterion in the credit assessment of fleets, the selection of trade routes and port investment plans. Despite this, many lenders still lack advanced physical risk quantification models, due to the complexity of climate data and the lack of granularity in the operational data of naval assets.

b. *Transition risk*

The transition to a low-carbon economy involves a set of significant risks for the shipping sector[138]. These risks, termed "transition risks," emerge in response to increasing regulatory, financial, technological, and social pressures to decarbonize. These risks can not only undermine the competitiveness of shipping companies, but directly affect asset values, cash flows, and operational resilience.

i. Regulatory and policy risks

Transition regulatory risks represent one of the most critical and pervasive dimensions for the shipping industry, as they stem directly from policies adopted at the international, regional, and national levels to accelerate the decarbonization of shipping. These risks manifest themselves through the introduction of new environmental regulations, emission limits, carbon taxation schemes and

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[136] Organisation for Economic Co-operation and Development. (2022). *Decarbonising maritime transport: Pathways to zero-carbon shipping by 2050*
[137] International Maritime Organization. (2020). *Fourth IMO GHG Study 2020*
[138] International Maritime Organization (2023), *2023 IMO Strategy on Reduction of GHG Emissions from Ships*

technical standards, with significant impacts on operational compliance, cost structure and shipowners' profitability. The International Maritime Organization (IMO) adopted a revised strategy on GHG emissions in 2023, which calls for carbon neutrality by 2050 and a 70 percent reduction in average emissions per ship by 2040 (compared to 2008 levels)[139]. Key measures adopted include:
- EEXI - Energy Efficiency Existing Ship Index[140]: imposes minimum energy efficiency limits for all existing ships above 400 GT. The regulatory impact of EEXI is twofold. On the one hand, it pushes shipowners into costly retrofits (e.g., engine derating, hull optimization, high-efficiency propellers) to obtain the certification needed to continue sailing legally. On the other, it forces older fleets, often operating on marginal routes or for small-scale operators, to consider early phase-out, with potential capital impacts (stranded assets) and reduction of available capacity in the market.
- CII - Carbon Intensity Indicator[141]: This system has more dynamic effects than EEXI, as it mandates continuous monitoring and improvement of emission performance. It obliges ships to annually classify their carbon intensity (class A-E). Ships classified as Class D or E for three consecutive years are subject to mandatory corrective action, or else they will be banned from certain ports or trading routes. This forces shipowners to change operating practices (e.g., slow steaming, route optimization) and integrate carbon management into daily business strategy, thus elevating management complexity.

In 2023, the EU included the maritime sector in the EU Emissions Trading System (ETS)[142], obliging operators to:

- purchase CO_2 allowances for each ton emitted (average price: 80-100 €/ton),
- monitor and verify emissions from ships over 5,000 GT that dock in European ports.

Starting in 2025, 100% of intra-EU emissions and 50% of emissions on international routes with origin or destination in an EU port will be covered[143]. This measure has tangible effects on marginal transportation costs, which can increase by more than 10-15% for some routes. The imposition of a fixed carbon price on bunker fuel pushes shipowners to reevaluate the efficiency of their fleets and to review their charter contracts (time charter, bareboat). It also generates a competitive risk: operators with older, less efficient fleets pay more dues, becoming less attractive to industrial customers.

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[139] DNV (2023), *Maritime Forecast to 2050*
[140] https://www.dnv.com/maritime/insights/topics/eexi/
[141] https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/
[142] European Commission (2023), *EU ETS Directive – Maritime Inclusion*
[143] Transport & Environment (2023), *Maritime ETS briefing note*

In addition, the FuelEU Maritime Regulation[144] imposes targets to reduce the carbon intensity of fuels used (-2% to 2025, -6% to 2030, -80% to 2050) and promotes the use of shore-side electricity (electrification in ports). This regulation pushes toward a forced transition of fuels in the medium to long term. However, the availability of alternative fuels is still limited, as is the refueling infrastructure in ports. Shipowners thus face a structural compliance risk, where even the mere technical availability of fuel may not be sufficient to meet the regulatory obligation. In addition, the electrification requirement in ports imposes infrastructure investments on shipowners and terminal operators, with risks of operational blockages in less equipped ports.

Another regulatory risk lies in the fragmentation of international regulatory plans; while IMO is proposing a long-term consensual strategy, regions such as the European Union, California, or Singapore are imposing more ambitious and regionalized rules. This generates overlap between systems (e.g., EU ETS vs. IMO MRV), duplicative obligations, and uncertainty about which standards will become dominant. This situation of regulatory inconsistency poses a high risk for shipowners, who must operate global fleets on routes that cross vastly different jurisdictions. Investment decision-making processes are affected: the choice of fuel, engine type, retrofit, or new ship design becomes a regulatory gamble. The risk is to invest in a technology that is compatible today but not accepted in strategic markets tomorrow.

Risk related to carbon taxation and market instruments plays an important role. Policies based on carbon pricing (ETS, carbon tax, fuel levy) pose new challenges to the industry. IMO is considering the introduction of a global economic mechanism for decarbonization, such as a carbon levy or a mandatory climate fund, estimated at about $100 per ton of CO_2[145]. The goal is to reduce the cost gap between conventional and alternative fuels by financing the technology transition.

The introduction of a global taxation system would be a structural breakthrough for the maritime economy, as it would eliminate many regional arbitrages. However, it creates major concerns among shipowners, especially in emerging markets, who fear a penalty to their competitiveness. Moreover, it is not yet clear how these resources will be redistributed, nor what impact they will have on the final cost of transportation for low-value goods (such as raw materials)[146].

Expected effects include:

- Increased bunkering costs,
- Need to internalize the cost of CO_2 in transportation contracts (pass-through), and

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[144] FuelEU Maritime Regulation (EU) 2023/1805

[145] Lloyd's Register & UMAS (2020), *Zero-Emission Vessels Transition Pathways*

[146] Stopford, M. (2020), *Maritime Economics*, 4th ed., Routledge

- Market distortions between compliant and non-compliant operators.

An additional regulatory risk is related to the enforcement capacity of new regulations: The effectiveness of environmental regulations depends on the enforcement capacity of different flag states (flag states) and ports. In many cases, controls are lax or easily circumvented. This exposes the industry to “regulatory arbitrage” practices (e.g., changing flags to more permissive registries, secondary routes to avoid regulated areas).
Asymmetry in regulatory enforcement creates an unfair competitive differential in favor of less compliant operators. It also undermines the credibility of the regulatory system itself. Compliant shipowners are thus penalized economically, while non-compliant ones can continue to operate by exploiting legal loopholes. This reduces the effectiveness of global environmental policies and creates a strong incentive for “race to the bottom” among ship registries.

ii. Technological risks

The transition to a low- or zero-carbon maritime sector represents one of the most radical transformations in the history of modern shipping. This transition is fueled by the urgency of reducing climate-altering emissions, in line with international climate change targets, but is highly dependent on the ability to develop, adopt, and integrate new energy and propulsion technologies. However, this very dependence on technology introduces several structural and systemic risks that can undermine both the operational feasibility and financial sustainability of the decarbonization pathway[147].
A first central issue is uncertainty about the energy carriers of the future. Currently, there is no single or dominant standard for alternative fuels in the maritime sector. Options under development include green ammonia, liquid hydrogen, synthetic methanol, bio-GNL, and e-fuels produced from renewable energy. Each of these fuels has different advantages and critical issues: ammonia, for example, is carbon-free but highly toxic and corrosive; liquid hydrogen has high theoretical efficiency but requires extreme storage conditions (-253°C); green methanol is more manageable but has low energy content per volume[148]. In the absence of clear regulatory and industrial direction, shipowners face a risk of technological lock-in: choosing a technology today that may not be the dominant one in the medium to long term carries the danger of tying up capital in assets that are potentially not compatible with future standards or available port infrastructure. The implications of this uncertainty are significant: there is decision blockage on the part of many operators, who prefer to postpone

[147] DNV. (2023). *Maritime Forecast to 2050*. Det Norske Veritas
[148] DNV & Ricardo. (2023). *Fuel for the Future: Decarbonising Shipping*. Study for the International Maritime Organization

investments to reduce the risk of strategic error, at the cost of losing competitive advantages in more environmentally demanding markets (such as Europe or North America)[149]. In addition, there is a risk of increasing dependence on political scenarios and temporary public incentives, making industrial planning highly vulnerable to regulatory changes. This is compounded by the limited technological maturity of many solutions being adopted. Maritime fuel cells, hybrid propulsion systems, and onboard carbon capture technologies are still at an intermediate level of development (TRL - Technology Readiness Level), not sufficiently tested on an industrial scale or on long-distance ocean routes[150]. This condition generates an operational performance risk: technologies may not provide adequate levels of reliability, autonomy or resilience to extreme maritime conditions, potentially affecting safety, service continuity and commercial reputation. Here again, the implications are multiple; On the one hand, increased technical risk may translate into higher insurance premiums for ships equipped with experimental technologies; on the other, it imposes the employment of highly specialized personnel and the need to invest in advanced training, with a not insignificant impact on the cost structure. In extreme cases, the failure of unconsolidated systems could cause property damage or service interruptions, exposing the company to contractual liabilities.

An additional risk is the inadequacy of port infrastructure to support the new fuels[151]. The transition requires major commercial ports to be able to offer bunkering services for ammonia, hydrogen or methanol, as well as electrification systems for berthed ships (cold ironing). However, most ports globally have not yet planned or begun work on such infrastructure upgrades. This shortcoming can generate logistical bottlenecks, increased dwell times, and additional costs related to the need for double bunkering, as well as a sharp reduction in the operational flexibility of zero-emission fleets, which risk being able to operate only on limited and predetermined routes[152]. The consequences of this infrastructure gap are significant. Green ships may have to limit their routes to equipped ports only, drastically reducing operational and commercial flexibility. There is also a risk of increased waiting times and logistics costs at the few available terminals, with negative effects on supply chain efficiency[153]. To make up for these rigidities, many operators may opt for hybrid (dual-fuel) solutions, but these increase the technical and managerial complexity of the ship.

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[149] Rehmatulla, N., Smith, T., & Wrobel, P. (2022). Cost competitiveness of alternative marine fuels. *Transportation Research Part D: Transport and Environment*, 113, 103503.

[150] Gkonis, K. G., & Psaraftis, H. N. (2020). Alternative fuels for maritime transport: Pathways, options, and perspectives. *Maritime Business Review*, 5(2), 137–152.

[151] Zhang, Y., & Zhang, J. (2024). Decarbonization of maritime ports: Infrastructure challenges and strategies. *Ocean & Coastal Management*, 245, 106728.

[152] Zhang, Y., & Zhang, J. (2024). Decarbonization of maritime ports: Infrastructure challenges and strategies. *Ocean & Coastal Management*, 245, 106728.

[153] Scown, C. D., Horvath, A., & McKone, T. E. (2022). Life-cycle assessment of onboard carbon capture systems for maritime transport. *Journal of Cleaner Production*.

The high cost of investment is another critical dimension. Building an alternative propulsion vessel can cost 30-100% more than a conventional vessel[154], while retrofitting existing fleets requires substantial capital to adapt engines, tanks, and safety systems. This implies significant financial risk, as investments must be sustained in an environment of regulatory uncertainty, volatility in transportation markets, and lack of stable price signals on green fuels. In addition, many shipping companies, particularly those of medium or small size, do not have sufficient financial capacity to sustain the transition without forms of government support or industry partnerships. Indeed, in this context, less capitalized companies' risk being unable to access the credit market or having to turn to more expensive and selective instruments such as green bonds or sustainability-linked loans, which require highly structured ESG plans. In parallel, many companies will have to redefine their business models, moving toward premium or high value-added segments to justify the higher costs. In a worst-case scenario, one can assume an industry selection process that will favor large global players at the expense of small regional fleets.

Finally, the technological complexity of the transition implies an increasing dependence on third parties: technology providers, specialized shipyards, alternative fuel producers, and port authorities[155]. This dependence can turn into a systemic risk, especially in the absence of harmonized international standards and shared technology governance. If a technology developed in partnership does not achieve the expected results or is excluded from the market, the investment risks turning into a sunk cost, compromising the shipowner's capital strength and the bankability of future projects.

In summary, technological risks are a central element in the transition of the shipping industry. They arise not only from the difficulty of developing new solutions, but more importantly from the interplay of technological uncertainty, high costs, infrastructural dependence, and lack of global standardization. An effective risk management strategy will necessarily need to integrate technical expertise, investment capacity, operational flexibility and strong coordination between public and private actors. Only in this way will it be possible to transform technological risk into an opportunity for innovation and sustainable competitive advantage.

iii. Economic and Financial Risks

In the context of the maritime sector's energy transition, it's pertinent to understand the economic and financial risks that derive, through transmission channels, from the direct and indirect impacts of

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[154] Rehmatulla, N., Smith, T., & Wrobel, P. (2022). Cost competitiveness of alternative marine fuels. *Transportation Research Part D: Transport and Environment*, 113, 103503.

[155] Scown, C. D., Horvath, A., & McKone, T. E. (2022). Life-cycle assessment of onboard carbon capture systems for maritime transport. *Journal of Cleaner Production*.

regulatory, technological, and market dynamics on operators' profitability, capital access, and financial stability. A primary pressure point is the rising operational costs due to the progressive adoption of alternative fuels—such as green methanol, ammonia, or bio-LNG—which are significantly more expensive than conventional fossil fuels[156]. Additionally, increased expenses related to environmental compliance (certifications, emissions monitoring, technical adjustments) further erode profit margins, particularly on low-value-added routes like dry bulk or petroleum product transport. This cost pressure may compel companies to renegotiate transport contracts, attempting to pass on additional costs to clients through carbon cost pass-through clauses. However, the market may not always absorb these increases, risking competitiveness loss against less regulated competitors or other logistics providers.

Beyond operational cost hikes, there's an unprecedented capital requirement to finance the construction of zero-emission vessels or retrofit existing fleets. Alternative fuel-powered ships can cost 30% to 50% more than conventional ones[157], and retrofitting entails prolonged technical downtimes and complex interventions on engines, tanks, and auxiliary systems. This exposes operators to excessive debt risks, especially amid rising global interest rates, diminishing their capacity to manage future financial obligations. Simultaneously, financial institutions— increasingly bound by ESG criteria and international guidelines—are more rigorously selecting projects to finance, favoring those with robust decarbonization strategies and climate transparency.

In this scenario, the Poseidon Principles play a crucial role. Launched in 2019 by a consortium of international financial institutions, this voluntary initiative aims to align ship finance portfolios with the IMO's and Paris Agreement's climate goals. Signatory banks—now representing over 60% of global maritime financing—commit to annually measuring and disclosing the carbon footprint of their financed fleets, assessing each client's alignment with decarbonization trajectories. The Poseidon Principles have fundamentally shifted maritime credit logic: evaluating traditional financial risk (cost, profitability, guarantees) is no longer sufficient; a climate-related metric must be integrated, compelling shipping companies to adopt credible emission reduction strategies to maintain capital access

Implications for shipowners are manifold[158]: the need for certifiable environmental monitoring and reporting tools (e.g., MRV, IMO DCS) and the urgency to restructure industrial plans toward climate

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[156] DNV & Ricardo. (2023). *Fuel for the Future: Decarbonising Shipping*. Study for the International Maritime Organization

[157] Hakirevic Prevljak, N. (2024, December 13). Poseidon Principles: Global shipping finance portfolio nears alignment with 2050 net zero goals. *Offshore Energy*.

[158] Cardenas, V. (2024). *Financial climate risk: a review of recent advances and key challenges*.

objectives consistent with financiers' expectations. Without such alignment, companies risk facing more onerous credit conditions, exposure limits, or outright exclusion from signatory banks' portfolios. Consequently, the Poseidon Principles act as an indirect yet effective pressure mechanism, accelerating the internalization of climate risk within the financial system and gradually redirecting investments toward low-emission technologies and fleets. For companies aiming to ensure medium- to long-term economic solidity, embracing this transparency and continuous environmental performance improvement framework is no longer a strategic option but a prerequisite for securing investor trust and sustainable credit access.

This landscape heightens the risk of financial market exclusion for operators unable to meet emerging standards, fostering a growing divide between well-capitalized companies capable of crafting detailed ESG plans and smaller operators with limited resources. Another financial risk is the devaluation of high-carbon-intensity assets, particularly conventionally fueled ships that no longer comply with regulatory standards or client expectations. These vessels risk becoming stranded assets—economically obsolete or non-operational—leading to reduced company asset value and potential breaches of existing financial covenants. The difficulty in reselling or recycling such assets, coupled with the need for premature decommissioning, can result in direct losses and negatively impact the company's financial robustness, also transmitting risk to financial institutions holding them as collateral or within credit portfolios.

Finally, the transition introduces new uncertainties tied to green market volatility: alternative fuels lack stable supply chains, CO_2 prices fluctuate based on political and economic decisions, and maritime transport demand is subject to unpredictable geopolitical and macroeconomic dynamics[159]. In this context, investments in green technologies, though necessary, present a more uncertain risk-return profile compared to the past, complicating the development of reliable and attractive business plans for financiers. This may lead to investment slowdowns, under-investment trends, or conversely, over-investment in non-standardized technologies, resulting in economic losses if technical or regulatory failures occur. In summary, the economic and financial risks of the transition are not merely managerial challenges but potential systemic destabilization factors for a globalized, capital-intensive sector like shipping. Only an integrated strategy—grounded in solid risk analysis, active engagement with financial institutions, and transparent climate governance—can ensure the bankability of future projects and the economic sustainability of maritime decarbonization.

[159] Cost competitiveness of alternative marine fuels. *Transportation Research Part D: Transport and Environment*, 113, 103503.

iv. Market and Reputational Risks

In the pursuit of decarbonization, the shipping industry faces not only regulatory, technological, and financial risks but also increasingly significant market and reputational risks. These risks influence competitiveness, commercial stability, and public perception of shipping companies. They stem from rapidly changing customer preferences, growing stakeholder pressure, and the escalating importance of environmental sustainability in contractual decisions and global supply chain management.

A notable aspect is the shift in demand from B2B clients, especially large multinationals, freight forwarders, and shippers operating under stringent ESG criteria. These entities increasingly incorporate requirements related to carbon intensity, emissions transparency, and demonstrable environmental commitment into their procurement processes. Shipping companies failing to meet these expectations risk exclusion from strategic long-term contracts and high-value logistics networks, directly impacting revenue and commercial relationships. This shift also reflects a preference for operators utilizing modern fleets powered by alternative fuels or possessing advanced environmental certifications. Companies lacking innovation or transparency may face marginalization, despite operational efficiency, due to insufficient environmental credibility.

Financial, insurance, and regulatory stakeholders are increasingly evaluating environmental performance in reputational terms. Failure to publish emissions data, absence of formal climate commitments, or instances of greenwashing can severely damage a company's reputation, affecting market demand, credit access, counterparty risk perception, and inclusion in ESG indices or sustainable investment funds. In the traditionally opaque shipping sector, reputation becomes a critical competitive asset. Companies positioning themselves as pioneers in the green transition gain strategic advantages not only with clients but also with regulators and the financial system.

A particularly critical issue is the rising risk of greenwashing—misleading or overly optimistic communication of environmental performance without substantive operational or technical backing. In shipping, greenwashing can manifest in various forms[160]: publishing climate goals unsupported by credible investment plans, promoting "alternative" fuels with significant lifecycle emissions, or using self-referential certifications and non-transparent emissions calculations.

While such practices may yield short-term reputational benefits, they expose companies to serious credibility risks, especially as climate transparency pressures intensify. Organizations like the Carbon Disclosure Project (CDP), the Global Logistics Emissions Council (GLEC), and ESG rating agencies are enhancing verification mechanisms, explicitly penalizing discrepancies between narrative and

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[160] United Nations. *Greenwashing – the deceptive tactics behind environmental claims*

reality (Financial Times, 2025)[161]. Thus, greenwashing is not merely an ethical or communication risk but a potential economic threat, jeopardizing financing access, tender participation, and stakeholder relationships.

Moreover, its impact can be amplified by media virality and growing social sensitivity to environmental issues, rendering companies engaged in such practices vulnerable to long-term, sometimes irreversible, reputational damage. Adopting certified disclosure tools, independent environmental audits, and transparent metrics—such as Scope 1, 2, and 3 emissions monitoring—is now a measure of reputational risk management and a strategic responsibility.

Another significant aspect is the commercial devaluation of fleets based on market perception. High-emission vessels, even if still compliant with regulations, may be deemed "brown assets," leading to progressive devaluation in charter agreements, insurance contracts, or secondary negotiations. This reduces the residual value of investments and increases the opportunity cost compared to adopting more sustainable solutions.

Therefore, this is not solely an image risk but a tangible industrial and commercial positioning risk. In a context where climate transparency is becoming a prerequisite for participating in major international trade flows, adopting advanced environmental practices, verifiable reporting tools, and sustainability-oriented strategic partnerships is essential for maintaining and expanding market presence.

In summary, market and reputational risks in shipping's transition should not be viewed as secondary externalities but as structural and determining factors in shaping the sector's future competitiveness. Companies that perceive sustainability not merely as a constraint but as an opportunity for relational, commercial, and identity innovation will be better positioned to enhance long-term resilience in an increasingly attentive, transparent, and environmentally responsible global landscape.

v. Risks Associated with Asset Obsolescence

Among the most critical and cross-cutting risks in the maritime sector's energy transition is the accelerated obsolescence of naval assets. This structural dynamic is profoundly redefining the economic value and operational horizon of maritime fleets. This risk materializes when a vessel, though still technically operational, becomes non-competitive, non-compliant with current

[161] Financial Times. (2025, April 17). *ESG verification frameworks tighten to penalize discrepancies*. Financial Times. Retrieved from https://www.ft.com/

environmental regulations, or simply undesired by the market, thereby losing its capacity to generate income or be efficiently utilized.

Several factors contribute to this obsolescence: the tightening of international and regional emission regulations—such as the Carbon Intensity Indicator (CII), Energy Efficiency Existing Ship Index (EEXI), FuelEU Maritime, and the inclusion of shipping in the European Union Emissions Trading System (EU ETS); the evolution of customer preferences towards operators with decarbonized fleets; the proliferation of Environmental, Social, and Governance (ESG) criteria in the selection of commercial and financial counterparts; and the acceleration of technological advancements rendering traditional propulsion systems rapidly outdated[162]

The combined effect of these factors leads to the premature devaluation of many currently operational ships, particularly those powered solely by fossil fuels and lacking dual-fuel systems or adequate technological retrofits. This phenomenon mirrors the concept of "stranded assets" in the energy industry—physical assets that, due to regulatory or market transformations, become unusable or economically worthless well before the end of their technical life (Caldecott et al., 2013).[163]

The economic and strategic implications are profound. Shipping companies are compelled to decommission vessels ahead of schedule, often without fully amortizing their investment, directly impacting their balance sheets and financial structures. In some instances, asset devaluation may lead to breaches of banking covenants or necessitate extraordinary provisions, thereby diminishing the capacity to secure financing for future investments.

Furthermore, the diminished marketability of obsolete ships adversely affects the secondary market. Vessels that previously could have been sold or chartered in other market segments—such as cabotage, short-sea routes, or emerging markets—now struggle to find employment due to the increasing environmental scrutiny from even smaller operators. Consequently, the residual value of these ships tends toward scrap value, which is not only significantly lower than their book value but also entails environmental and logistical costs associated with dismantling, often concentrated in countries with questionable environmental and social standards[164]

Another significant collateral effect is the shortening of investment horizons. Whereas ships were traditionally designed and evaluated over a 25–30-year lifecycle, shipowners and financiers now often operate within much shorter timeframes—between 10 and 15 years—due to concerns that regulatory

[162] European Commission. (2023). *FuelEU Maritime Initiative*.

[163] Caldecott, B., Tilbury, J., & Ma, Y. (2013). *Stranded assets and the fossil fuel divestment campaign: what does divestment mean for the valuation of fossil fuel assets?* Smith School of Enterprise and the Environment, University of Oxford.

[164] UNEP. (2020). *Green Jobs: Towards decent work in a sustainable, low-carbon world*. United Nations Environment Programme

or technological changes may swiftly erode the commercial relevance of assets[165]. This temporal compression directly impacts the financial structure of investments, making long-term financing more challenging and increasing the weight of speculative components and market risks.
Moreover, a vicious cycle between technological risk and obsolescence emerges: the fear of investing in the "wrong" technology may lead operators to delay fleet renewal, but such inaction increases the risk of falling behind the market, creating a technological gap that is difficult to bridge[166]. For banks and investors, this necessitates an increasing integration of climate metrics and environmental risk horizons into credit assessments to avoid exposure to portfolios overly concentrated on high-devaluation-risk assets. From a commercial standpoint, asset obsolescence also entails a loss of contractual appeal. Charter companies and major global shippers tend to select vessels that offer not only economic efficiency but also certified environmental performance. A ship that does not meet new regulatory requirements or lacks emission monitoring systems risks exclusion from certain routes, markets, or logistics chains, regardless of its technical condition or cargo capacity. This market selection, increasingly guided by ESG criteria and contractual sustainability constraints, accelerates a "reward and penalty" process that effectively assigns growing value to environmental efficiency as a component of a ship's asset value[167]. In this context, the risk of obsolescence becomes a strategic variable requiring active management through careful fleet renewal planning, accurate assessment of compatible future fuels, integration with port infrastructure, and the adoption of flexible financial models that explicitly consider the possibility of a shortened useful asset life. In summary, the energy transition necessitates not only changes in business models and technological choices but also imposes a new culture of asset management, wherein a ship's economic longevity is increasingly tied to its adaptability to a decarbonized, transparent, and resilient maritime system.

c. *Reputational risk*

Reputational risk is often underestimated compared to physical and transition risks, but it can generate significant impacts, both in terms of loss of intangible value and erosion of the customer base. This risk occurs when a bank is perceived as inconsistent with its sustainability commitments, or when it finances businesses or projects associated with environmental damage, regulatory violations, or unfair practices.
In the maritime sector, reputational implications are heightened for several reasons:

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[165] IMO. (2023). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*.
[166] Lloyd's Register. (2023). *Decarbonization: Managing technology risk in shipping*.
[167] Woodrow. (2023). *Navigating ESG Risks in the Maritime Sector*.

- Increased public visibility of emissions from ships and trade routes through vulnerable ecosystems (e.g. Arctic).
- Growing media sensitivity towards "brown" shipping (based on fossil fuels), amplified by campaigns by NGOs, stakeholders and international media.
- Pressure from ESG (Environmental, Social and Governance) investors, who require consistency between financing policies and stated climate targets.

For banks, this risk materializes in several ways:

- Erosion of confidence by institutional investors and retail customers, resulting in a decline in assets under management (AUM).
- Loss of access to international capital, such as that mobilized through green bonds, sustainability-linked loans or transition funds.
- Increased compliance and disclosure costs, required to restore transparency and credibility.

Reputational risk is particularly relevant in the current context, in which banks are called upon not only to reduce financed emissions, but also to effectively communicate the progress made and the metrics adopted. The lack of consistency between external communication and actual performance can expose institutions to greenwashing perception, with a consequent deterioration of the public image and competitive position.

2.3. Transmission of Climate-Related Risks in the Maritime Sector into Existing Banking Risk Drivers

In the shipping sector, climate risks – whether physical (extreme weather events, sea level rise) or transition (new regulations, carbon taxation, technological innovations) – are directly reflected in the main drivers of banking risk: credit risk, market risk, reputational risk and operational risk. Banks, particularly those with significant exposure to the shipping sector, are now called upon to update their internal risk assessment models to effectively integrate these factors into credit pricing, expected loss measurement and capital allocation strategies.

2.3.1. Credit risk and probability of default (PD)

Climate risks influence the probability of default of shipping companies through numerous channels. Physical risks, such as extreme weather and sea events or the increase in global average temperature, can compromise the operation of routes, damage critical infrastructure and cause disruptions in trade flows. Transition risks, such as the introduction of the EU ETS in maritime transport (from 2024) or the new energy efficiency thresholds imposed by the IMO, lead to increased operating costs and an accelerated devaluation of non-compliant ships, especially those powered by traditional fossil fuels.

To integrate these factors into risk models, banks adhering to the Poseidon Principles use a quantitative measurement system of the environmental performance of the ships financed. This is a voluntary initiative born in 2019, which has been joined by some of the leading international banks active in ship financing. The aim of the framework is to align the credit portfolios of the maritime sector with the objectives of the International Maritime Organization (IMO), which envisage a 50% reduction in greenhouse gas emissions by 2050 compared to 2008 levels. The operation of the Poseidon Principles is based on the annual collection of data on CO_2 emissions from each funded ship, via the IMO's mandatory Data Collection System (DCS). These data are used to calculate the Annual Efficiency Ratio (AER), i.e. the carbon intensity per tonne of cargo transported per nautical mile. The value of the EAR, weighted across the entire funded portfolio, is then compared to a reference trajectory defined by the IMO, generating a climate alignment score. A negative deviation from the target trajectory indicates a portfolio that complies with or outperforms the targets; on the contrary, a positive value signals insufficient environmental performance. This indicator is actively used by banks to guide credit policies: for example, by rewarding the most efficient fleets with preferential financing conditions, or by penalizing the most polluting ones with higher capital requirements or exclusion from the active portfolio[168]

From a technical point of view, this tool allows an initial structured integration of climate risk into the origination, monitoring and reporting processes of naval credit, and can be directly linked to IRB (Internal Ratings-Based) models through the updating of PD and LGD parameters based on the emission profile of the counterparty.

2.3.2. Market risk and collateral write-down

The market value of ships can change significantly if the asset becomes non-compliant with environmental standards. A ship rated with a low CII rating (D or E) may no longer be allowed on highly regulated routes or require costly retrofits to maintain operations. This dynamic has a direct impact on loan-to-value (LTV) and loss given default (LGD), fundamental parameters in banks' risk models.

Alongside sectoral instruments such as the Poseidon Principles, the EU Taxonomy has introduced a general and legally binding system for classifying sustainable economic activities, with a cross-cutting impact on all sectors, including maritime transport. Introduced with Regulation (EU) 2020/852[169], the Taxonomy establishes strict technical criteria that an activity must meet in order to

[168] Poseidon Principles Association. (2023). *Annual Disclosure Report 2023*.

[169] European Commission. (2020). *Regulation (EU) 2020/852 of the European Parliament and of the Council on the establishment of a framework to facilitate sustainable investment (EU Taxonomy)*.

be considered "sustainable" from an environmental point of view. As far as shipping is concerned, these criteria include compliance with CO_2 emission thresholds, compliance with international standards such as the Energy Efficiency Design Index (EEDI)[170]or the Carbon Intensity Indicator (CII)[171],and the adoption of low-carbon alternative fuels, such as bio-LNG, hydrogen or ammonia. However, the conformity assessment is not limited to the technical parameter alone: each activity must contribute substantially to at least one of the EU's six environmental objectives, without causing significant harm to the others (DNSH – Do No Significant Harm principle)[172], and must comply with minimum social criteria in line with OECD guidelines[173] and ILO conventions[174]. For banks, the impact of the Taxonomy is especially relevant in determining the Green Asset Ratio **(**GAR**)**, i.e. the percentage of financed assets classified as "aligned"[175].This indicator has direct consequences on the institution's reputation, on the ESG assessment by investors and on access to green financing instruments such as sustainable covered bonds or EIB (European Investment Bank) credit lines[176]. However, despite the ambitious regulatory framework and the intention to provide a common methodology for assessing the sustainability of a naval asset not only from a technical-engineering point of view but also in relation to systemic environmental impacts and European regulatory obligations, it has several substantial critical issues, widely discussed both in the academic and professional[177] spheres, in particular, from the point of view of technical and sectoral applicability. One of the main weaknesses lies in the lack of granularity in the technical specifications provided for many economic activities. In many cases, the regulation provides general criteria but does not articulate sufficiently detailed operating standards for each production sector. This phenomenon is clear in the maritime sector, where there is a lack of precise guidance on crucial aspects such as hybrid propulsion technologies, bio-based fuels, retrofit solutions for improving energy efficiency, and vessel lifecycle management. The result is regulatory uncertainty that hinders the full integration of the Taxonomy into the decision-making processes of companies and financial operators. The practical application of the "Do No Significant Harm" (DNSH) principle is particularly problematic. The structure of the DNSH requires that any economic activity, to be considered "sustainable", does

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[170] IMO – International Maritime Organization. (2013). *Resolution MEPC.203(62): 2013 Guidelines on the method of calculation of the attained EEDI*

[171] MO – International Maritime Organization. (2021). *Resolution MEPC.328(76): Amendments to MARPOL Annex VI introducing CII*

[172] EU Technical Expert Group on Sustainable Finance (TEG). (2020). *Taxonomy Technical Report: Technical Annex*.

[173] OECD – Organisation for Economic Co-operation and Development. (2011). *OECD Guidelines for Multinational Enterprises*.

[174] ILO – International Labour Organization. (2023). *Core Conventions and Recommendations*.

[175] EBA – European Banking Authority. (2022). *Final Draft Implementing Technical Standards on prudential disclosures on ESG risks in accordance with Article 449a CRR*

[176] EIB – European Investment Bank. (2023). *Sustainability Funding Strategy Report 2023*.

[177] https://climateimpact.edhec.edu/charting-pathway-transition-finance-lessons-eu-framework

not cause significant harm to any of the other five environmental objectives other than the one to which it mainly contributes (mitigation, adaptation, sustainable use of water and marine resources, circular economy, pollution prevention, protection of biodiversity). However, the systemic interdependence between these objectives makes it extremely difficult, if not impossible, to ensure impact neutrality. For example, an activity that aims to decarbonise through the use of biofuels can generate indirect negative effects on biodiversity or land consumption; Similarly, the adoption of high-efficiency technologies may imply the use of critical materials with significant environmental impacts along the value chain. In this context, DNSH is conceptually weak and operationally ambivalent, risking translating into an overly formal or worse, arbitrary assessment.

These structural gaps reduce the functionality of the Taxonomy as an operational tool to support investment decisions, risk management and capital allocation. In the absence of comprehensive technical criteria and a truly applicable DNSH framework, financial actors find themselves having to interpret and integrate the criteria subjectively, with the risk of heterogeneity in valuation methods, low comparability between operators and potential distorting effects on sustainability reporting (e.g. in the calculation of the Green Asset Ratio). The consequence is a loss of regulatory effectiveness, which risks undermining the very objective of the Taxonomy: to create trust and transparency in the sustainable capital market.

2.3.3. Operational risk and ESG compliance

Climate risk management requires banks to develop information systems and organizational processes that can capture, verify and integrate reliable ESG data related to counterparties. The main critical issues concern the availability of standardized data, the traceability of Scope 1, 2 and 3 emissions of the financed companies, staff training and the integration of information flows into management systems.

In this context, the third pillar that completes the current framework of climate risk analysis is represented by the CSRD – Corporate Sustainability Reporting Directive[178], which has significantly expanded the non-financial reporting obligations for companies[179]. In force from 2023 and progressively applicable according to the size of the companies, the directive requires the use of common technical standards, the ESRS (European Sustainability Reporting Standards), to ensure the comparability and reliability of ESG data[180].

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[178] European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD)*.
[179] European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD).*
[180] European Financial Reporting Advisory Group (EFRAG). (2023). *ESRS E1 – Climate Change*.

Companies subject to the CSRD, including shipping companies, shipyards and port operators, must publish detailed information on Scope 1, 2 and 3 emissions, climate transition plans, the distribution of CAPEX and OPEX in sustainable activities (Taxonomy-aligned), as well as the environmental and social impacts of their activities. One of the most innovative elements introduced by the directive is the principle of double materiality, according to which companies must report both the impacts of climate change on their economic and financial performance and the impact of their activities on the climate and society.

For banks and pending the adoption of the Omnibus package[181] that simplifies CSRD, the directive represents a structural source of granular, standardized and verifiable ESG data, which is essential to feed internal ESG rating models, carry out climate scenario analyses and fulfill central banks European Banking Authority (EBA) and investors. The directive thus makes it possible to reduce the information asymmetry between companies and banks and to integrate sustainability into risk management processes in an objective, documented and measurable way (EFRAG, 2024).

However, the full potential of the CSRD framework is currently under pressure due to the Omnibus Package, introduced by the European Commission in early 2025. Designed to simplify sustainability reporting obligations and reduce administrative burdens, especially for small and medium-sized enterprises, the package introduces several changes that significantly affect data availability:

- The threshold for reporting obligations is raised to 1,000 employees, excluding many SMEs and reducing ESG coverage across the market;
- Sector-specific ESRS standards are delayed or simplified, weakening the granularity and precision of disclosed indicators;
- The application timeline is extended for companies in the second and third reporting waves, postponing the generation of critical ESG datasets to 2028 or later;
- The scope of corporate due diligence is narrowed (as part of the CSDDD), focusing only on Tier 1 suppliers and limiting transparency across value chains.

Collectively, these adjustments weaken the scope, reliability and standardization of ESG data streams flowing into the financial system, undermining banks' ability to perform accurate climate and sustainability risk assessments. Stakeholders such as Eurosif and ESG data providers have raised concerns that the Omnibus Package could increase the risk of greenwashing, slow down ESG integration in risk models, and hamper efforts to align financial flows with the EU Green Deal.

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[181] European Commission. (2023). *Proposal for a Directive amending Directive 2013/34/EU as regards the time limits for the adoption of sustainability reporting standards for certain sectors and for certain third-country undertakings (Omnibus proposal)*.

Taken together, the Poseidon Principles, EU Taxonomy and CSRD are not isolated tools, but integrated components of a multi-level analytical system. The technical data produced through the Poseidon Principles feed into portfolio metrics and guide financing strategies in the maritime sector[182]; the EU Taxonomy defines the technical thresholds and regulatory criteria to qualify financed activities as sustainable[183]; the CSRD ensures that all credit counterparties produce comparable, verifiable and consistent ESG data[184].

This regulatory and information ecosystem has radically transformed the logic of banking risk management, evolving sustainability from a purely reputational factor to a quantitative lever for creditworthiness assessment, capital allocation and asset management.

2.4. Transition Finance and Financing Instruments: Strategic Tools for Climate-Aligned Capital Allocation

Transition finance represents a flexible approach, designed to finance companies and projects that are not yet fully sustainable, but which are moving in a concrete and measurable way towards the transition[185]. It is particularly relevant for so-called "hard-to-abate" sectors, such as shipping, where the immediate adoption of net-zero technologies is technically complex and uneconomical. Unlike green bonds, which require the exclusive use of funds for "green" projects, transition finance instruments (whether on a dedicated finance basis or not) are based on assessing the credibility and consistency of transition plans. The European Commission's technical platform has provided guiding criteria for the identification of transitional activities: these must be clearly differentiable from business-as-usual, demonstrate a progressive improvement in climate impact, and crucially, must not generate a "lock-in effect"—that is, they should not lead to long-term dependence on carbon-intensive technologies or infrastructures that may hinder or delay the adoption of more advanced, zero-emission solutions in the future[186]. In practice, this means that transitional investments should be technologically flexible and compatible with future alignment to net-zero targets. For example, the financing of retrofitting operations that enable the use of bio-LNG or hybrid propulsion systems on existing vessels qualifies as transitional only if such retrofits are compatible with the eventual conversion to cleaner fuels (e.g., green ammonia or hydrogen) or full electrification. Conversely, financing that locks in the continued use of fossil-based systems without a credible pathway for

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[182] Poseidon Principles Association. (2023). *Annual Disclosure Report*.
[183] European Commission. (2020). *Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy).*
[184] European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD).*
[185] UNEP FI. (2021). Transition Finance Guide for Banks.
[186] EU Platform on Sustainable Finance. (2022). *Final report on social taxonomy*. European Commission.

upgrade or substitution would be excluded from transition finance eligibility, as it perpetuates carbon dependency and reduces strategic optionality for future innovation.

For banks, transition finance enables them to support clients on a realistic, staged path toward decarbonisation, maintaining credit exposure while incentivizing incremental, measurable improvements. By ensuring that financed activities do not create structural barriers to cleaner alternatives, financial institutions can manage long-term transition risk more effectively and align their portfolios with regulatory and market expectations for climate-aligned capital allocation.

In a nutshell, transition finance bridges the gap between brown and green activities, reducing the risk of economic discontinuity in the transition.

In this context of increasing regulatory and market pressure for rapid decarbonisation, the banking sector has begun to reorient credit supply through tools that link financial conditions to companies' environmental performance. These are tools that allow not only to reward virtuous behaviour from a climate point of view but also measuring and managing climate risk ex ante, integrating it into pricing models, capital allocation and credit granting processes. The main types of instruments in use today are sustainability-linked loans (SLLs) and sustainability-linked bonds (SLBs), green loans and bonds, and transition loans and bonds (both on a dedicated financing, general purposes, and transition-linked basis), transition Linked Loans and Bonds (TLLs/TLBs).

In this regard, the paper "Sustainable Finance in the Maritime Sector" by Biermans et al. (2023)[187] examines specific financial instruments applicable to decarbonization of shipping. Green Bonds and Sustainability-Linked Loans are bond instruments that link funding to environmental objectives, offering more favourable interest rates to companies that demonstrate progress in reducing emissions. Green Bonds are fixed-income financial instruments issued by companies, governments or financial institutions to raise capital exclusively for projects with positive environmental impacts. They operate like traditional bonds, with a fixed yield and a fixed maturity, but with the difference that the funds raised must be invested in sustainable initiatives. One of the key features of these instruments is that the use of proceeds is tied: the capital raised must be used for environmental projects such as energy transition, energy efficiency, sustainable transport or adaptation to climate change. Transparency is a key element in ensuring the credibility of green bonds, as issuers are required to provide regular reports on the use of funds and the environmental benefits achieved, often following recognised standards such as the Green Bond Principles (GBP)[188] of the International Capital Market Association

[187] Biermans, M. L., Bulthuis, W., Holl, T., & Overbeeke, B. (2023). Sustainable finance in the maritime sector. In M. Lind, W. Lehmacher, & R. Ward (Eds.), *Maritime decarbonization* (pp. 251–273). Springer.
[188] International Capital Market Association (ICMA). (2021). *Green Bond Principles*

(ICMA)[189] or the EU Green Bond Standard[190]. In the shipping sector, Green Bonds are used to finance the modernisation of ship fleets with zero-emission or hybrid ships, building infrastructure for the supply of alternative fuels such as hydrogen or green ammonia and improving energy efficiency in ports through electrification of docks. These instruments are becoming increasingly relevant for the decarbonisation of the maritime sector, as they enable shipowners to obtain financing on favourable terms to invest in sustainable technologies. Moreover, with the introduction of stricter environmental regulations such as the EU Emissions Trading System (EU ETS), access to Green Bonds is a strategic lever to ensure the long-term competitiveness of shipping companies. By mobilising private and institutional capital towards the ecological transition, Green Bonds are establishing themselves as one of the key tools for sustainable finance, helping to reduce the environmental impact of high-emission industries such as shipping.

Green Loans are financial instruments structured to exclusively finance or refinance eligible green projects that deliver clear environmental benefits. Much like Green Bonds, Green Loans are bound by a use-of-proceeds requirement: the loan capital must be allocated entirely to projects that meet specific environmental sustainability criteria. These instruments are governed by the Green Loan Principles (GLP), developed by the Loan Market Association (LMA) in collaboration with the Asia Pacific Loan Market Association (APLMA) and the Loan Syndications and Trading Association (LSTA). The GLP framework, updated in 2023, outlines four core components: the use of proceeds, the process for project evaluation and selection, the management of proceeds, and reporting[191].

In the maritime sector, Green Loans are increasingly used to support capital-intensive investments that align with the decarbonisation goals set by the International Maritime Organization (IMO) and the EU Green Deal. Typical examples of eligible activities include the purchase of low- or zero-emission vessels, such as those powered by hydrogen, ammonia, or battery-electric systems; the installation of alternative propulsion technologies, including air lubrication systems, carbon capture onboard units, or wind-assisted propulsion; and the construction or retrofitting of port infrastructure to support shore-side electrification and cleaner fuel bunkering (e.g., LNG or biofuels). For a loan to qualify as "green," the borrower must provide clear documentation that the financed project contributes to one or more environmental objectives, such as climate change mitigation, pollution prevention, energy efficiency, or biodiversity conservation. In addition, the borrower is

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[189] https://www.icmagroup.org

[190] https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/european-green-bond-standard-supporting-transition_en

[191] Loan Market Association (LMA), Asia Pacific Loan Market Association (APLMA), & Loan Syndications and Trading Association (LSTA). (2023). *Green Loan Principles*.

expected to implement transparent reporting mechanisms and, where feasible, obtain third-party verification to ensure that the funds are used in accordance with the GLP and deliver the expected environmental outcomes.

Green Loans offer strategic advantages to both borrowers and lenders: they often benefit from better pricing terms due to their ESG profile, and they enhance the environmental credentials of the financial institution's loan book, thus contributing to alignment with regulatory metrics like the Green Asset Ratio (GAR) under the EU Taxonomy[192].

Sustainability-Linked Loans (SLLs) are innovative financing instruments that directly tie the economic conditions of a loan, typically the interest rate, to the achievement of specific sustainability objectives by the borrower. Unlike Green Loans, which earmark capital for predefined environmentally sustainable projects, SLLs base their structure on the borrower's overall performance against a set of predefined Environmental, Social, and Governance (ESG) Key Performance Indicators (KPIs)[193].

In the maritime sector, these KPIs frequently relate to the reduction of greenhouse gas (GHG) emissions, the enhancement of fleet energy efficiency—measured through standardized indices such as the Energy Efficiency Design Index (EEDI), the Carbon Intensity Indicator (CII), or the Annual Efficiency Ratio (AER)—and the increase in the share of vessels powered by alternative fuels (e.g., bio-LNG, green methanol, ammonia, e-fuels). These performance goals are formally codified as Sustainability Performance Targets (SPTs) within the loan documentation. According to the Loan Market Association (LMA)[194] principles, these targets must be clearly defined, technically measurable, sufficiently ambitious, and subject to third-party verification.

The structure of SLLs enables borrowers to benefit from reduced interest rates—or other favourable financial terms—upon meeting the agreed SPTs. Conversely, failure to meet the targets results in an increase in the loan's cost through predetermined penalty mechanisms. This dual incentive system encourages the borrower to commit to concrete improvements in sustainability performance and facilitates a progressive internalization of climate-related externalities into credit pricing. From the lender's perspective, SLLs serve as an effective tool to mitigate transition risk within their loan portfolios. By contractually linking environmental performance to financial terms, banks reduce their exposure to future regulatory tightening, reputational degradation, and technological obsolescence of

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[192] European Commission. (2020). *Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy)*

[193] *Hapag-Lloyd. (2021). Sustainability-linked loan transaction with ING and Citi.*

[194] Loan Market Association (LMA), Asia Pacific Loan Market Association (APLMA), & Loan Syndications and Trading Association (LSTA). (2025, March 26). *Sustainability-Linked Loan Principles*.

financed assets. ESG risk is thereby transformed from an exogenous uncertainty into a quantifiable and manageable contractual variable. Operationally, SPTs are embedded into the financing agreements through interest rate step-up/down clauses (unlike SLBs where only step up applied), which define the margins by which the pricing of the loan will be adjusted based on sustainability performance. This structure generates a convergence between environmental objectives and financial incentives, aligning the strategic interests of both lender and borrower along a shared trajectory of decarbonization and ESG performance enhancement**.**

Sustainability-Linked Bonds (SLBs) are bond instruments that link funding to sustainable objectives. Unlike green bonds, which earmark proceeds for specific environmental projects, SLBs allow general-purpose financing while tying financial conditions—typically the bond's coupon—to the issuer's achievement of predefined sustainability performance targets (SPTs). If the issuer meets these targets within a specified observation period, the bond retains its base financial terms; however, if the issuer fails to comply, the bond activates a margin ratchet, generally in the form of a coupon step-up, increasing the cost of capital[195].

SLBs are gaining popularity across high-emission sectors, including shipping, as a flexible mechanism to mobilize capital in support of the energy transition—particularly in cases where projects may not yet qualify under EU Taxonomy definitions for "green" assets. According to the ICMA Illustrative KPIs Registry[196] (2024), common SPTs include the reduction of Scope 1, 2, and 3 greenhouse gas (GHG) emissions (expressed in tCO_2e per revenue or production unit), increased renewable energy consumption, improved energy efficiency metrics, circular economy targets, and reduction in product or fleet carbon intensity. In maritime transport, SPTs may focus on the average improvement of a company's Carbon Intensity Indicator (CII) or on the percentage of vessels operating with low-carbon alternative fuels such as bio-LNG, green methanol, or ammonia.

From a financial engineering perspective, SLBs typically include a coupon step-up mechanism—ranging from 25 to 100 basis points—that is triggered if the issuer fails to meet the SPTs by a specified date. This structure creates a dual incentive: it encourages the issuer to meet its sustainability commitments while offering bondholders a form of climate risk compensation should those commitments not materialize. However, the credibility of an SLB hinges on the robustness, relevance, and verifiability of the KPIs and targets chosen. The ICMA's guidance[197] requires that each SPT be tied to a clearly defined historical baseline, independently verified by a second-party opinion (SPO),

[195] Anthropocene Fixed Income Institute. (2023). *Sustainability-Linked Bond Handbook: Best Practices and Pitfalls in Linking Finance to Climate Objectives*.

[196] ICMA – International Capital Market Association. (2024). *Illustrative KPIs Registry – June 2024*.

[197] ICMA – International Capital Market Association. (2023). *Sustainability-Linked Bond Principles and Guidance*

and reported annually in a transparent and auditable manner. Targets should be ambitious, sector-specific, and aligned with broader frameworks such as the Science-Based Targets initiative (SBTi), the EU Taxonomy, or the CSRD.

The Anthropocene Fixed Income Institute (2023)[198] highlights the growing relevance of SLBs in investor portfolios and underlines the importance of strong structuring to avoid "greenwashing." The Institute recommends enhanced market discipline, better linkage between environmental performance and bond economics, and greater integration of SLBs into internal ESG rating methodologies and risk-adjusted capital allocation models. Moreover, SLBs should not be viewed solely as reporting tools, but as financial instruments capable of directly impacting the issuer's cost of capital and thus their transition trajectory.

In summary, Sustainability-Linked Bonds offer a powerful tool for aligning debt markets with long-term climate objectives. Their flexibility makes them particularly suitable for sectors where the transition to sustainability is complex and capital-intensive. The success of SLBs, however, depends on rigorous KPI design, reliable external verification, and a commitment to measurable, time-bound outcomes.

Transition Linked Loans (TLLs) are an emerging class of sustainable finance instruments designed to support companies operating in carbon-intensive sectors—commonly referred to as *hard-to-abate*—as they transition towards low- or zero-emission operating models. Among these sectors, maritime transport stands out as one of the most critical, both due to its significant climate footprint and the structural challenges it faces in achieving rapid compliance with net-zero targets[199]. TLLs differ from traditional Sustainability-Linked Loans (SLLs) in that they are specifically tailored to facilitate gradual and credible transition processes, rather than rewarding or penalising companies solely based on ESG performance indicators that assume a more advanced sustainability maturity[200].

The structure of a TLL is grounded in the development and validation of a Transition Pathway—a forward-looking, sector-specific climate strategy aligned with global decarbonisation goals and aligned with regulatory expectations, particularly those defined by the European Commission and the EU's Sustainable Finance Platform[201]. This pathway must be assessed by an independent third party and should include a time-bound roadmap with interim decarbonisation milestones, a capital

[198] Anthropocene Fixed Income Institute. (2023). *Sustainability-Linked Bond Handbook: Best Practices and Pitfalls in Linking Finance to Climate Objectives*.
[199] EU Platform on Sustainable Finance. (2022). *Final Report on Minimum Safeguards and Transition Finance*.
[200] Loan Market Association (LMA). (2023). *Sustainability-Linked Loan Principles and Guidance on Climate Transition Finance*.
[201] Biermans, M. L., Bulthuis, W., Holl, T., & Overbeeke, B. (2023). Sustainable finance in the maritime sector. In M. Lind, W. Lehmacher, & R. Ward (Eds.), *Maritime decarbonization* (pp. 251–273). Springer.

investment plan targeting clean or low-carbon technologies, and a phased phase-out strategy for high-emission activities[202]. In the case of shipping, relevant actions may include retrofitting engines to use bio-LNG, green methanol or ammonia; deploying digital tools for energy optimisation; and progressively replacing legacy fleets with vessels compliant with advanced EEDI and CII standards. Contractually, TLLs link the financial conditions of the loan—such as interest rate, tenor, or covenant flexibility—to the borrower's adherence to its transition plan. Unlike SLLs, however, the penalisation mechanism is structured to reflect the technical and economic constraints specific to the sector, thus avoiding overly punitive outcomes for companies that are genuinely committing to structural improvements but do not yet meet the thresholds of green classification under the EU Taxonomy[203].
For banks, TLLs represent a strategic solution for managing transition risk proactively within their loan portfolios. Rather than divesting from or excluding entire industrial sectors, banks can support clients through a verifiable and realistic decarbonisation journey, thereby improving the long-term resilience of their credit exposure. From a prudential perspective, TLLs reduce the risk of strategic misalignment with the expectations of the European Central Bank, providing traceable and auditable evidence of a firm's intent and capability to align progressively with the EU Taxonomy and EFRAG's transition plans' credibility criteria[204].

In a nutshell, TLLs are not designed to finance fully "green" activities, but rather function as bridging instruments that connect high-emission activities with the trajectory of sustainable finance. Their purpose is to enable transitions that are technically feasible, economically viable, and socially inclusive. Particularly in sectors like shipping, the widespread adoption of TLLs may play a decisive role in ensuring an orderly and effective transformation of the global industrial base.

Transition-Linked Bonds (TLBs) are an emerging class of performance-based debt instruments designed to finance the transition of carbon-intensive sectors toward low-carbon trajectories. Unlike Green Bonds, which finance environmentally eligible projects, or Sustainability-Linked Bonds (SLBs), which adjust financial terms based on corporate-wide ESG targets, TLBs are specifically structured to support companies engaged in a credible, time-bound, and science-based transition process, especially in *hard-to-abate* sectors such as shipping, steel, cement, and aviation.

The structure of TLBs is based on linking bond characteristics—typically the coupon rate—to the issuer's achievement of sector-specific Transition Performance Targets (TPTs). These targets are

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[202] EU TEG – Technical Expert Group on Sustainable Finance. (2020). *Taxonomy Report: Technical Annex*

[203] European Commission. (2020). *Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy)*

[204] EFRAG – European Financial Reporting Advisory Group. (2023). *European Sustainability Reporting Standards (ESRS)*

aligned with long-term decarbonisation pathways and reflect a company's adherence to a pre-validated transition strategy. Such strategies must be grounded in public climate commitments, aligned with net-zero trajectories (e.g., SBTi, IEA NZE), and validated through robust governance mechanisms and independent third-party assessments. Unlike SLBs, which may focus on operational KPIs such as energy intensity or emissions reductions, TLBs typically involve strategic structural changes, such as the introduction and implementation at vessel and/or fleet level of fuel switching, asset retrofitting, infrastructure adaptation, or full fleet transformation plans[205].

The objective of TLBs is to accelerate the flow of capital toward firms that are not yet aligned with green criteria but have adopted transparent and verifiable roadmaps to comply with climate targets over a defined time horizon. These bonds provide a transitional financing bridge, allowing issuers to access capital markets while progressing toward environmental alignment. From an investor's perspective, TLBs offer a risk-adjusted mechanism to fund transition with built-in safeguards and performance conditions.

On the regulatory side, while TLBs are not yet governed by a dedicated international framework like ICMA's Green Bond Principles or Sustainability-Linked Bond Principles, several initiatives are laying the groundwork for their standardisation. In particular, the EU Platform on Sustainable Finance has issued guidance on what qualifies as "transition finance," outlining core principles such as credible transition plans, science-based targets, transparency, and governance. Similarly, the OECD (2023)[206] and Climate Bonds Initiative (CBI)[207] are working on establishing taxonomies and disclosure templates to distinguish transition bonds from greenwashing attempts.

The financial characteristics of TLBs often include a coupon step-up mechanism, whereby the interest rate increases if the issuer fails to meet its intermediate decarbonisation milestones. In contrast, bondholders may benefit from stable or reduced coupon rates if targets are met or exceeded. This incentive structure aims to align the issuer's cost of capital with its climate transition performance.

In conclusion, Transition-Linked Bonds represent a key innovation in sustainable finance, enabling banks and institutional investors to support decarbonisation in sectors where green financing is not yet technically or economically viable. They fill the gap between conventional financing and full environmental alignment, contributing to a more inclusive and realistic pathway toward net-zero[208].

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[205] EU Platform on Sustainable Finance. (2022). *Final Report on Minimum Safeguards and Transition Finance*

[206] OECD. (2023). *Transition Finance: Investigating the State of Play – Lessons from Practitioners*.

[207] Climate Bonds Initiative. (2023). *Transition Finance Handbook*.

[208] International Energy Agency. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*.

In the evolving landscape of sustainable finance, Transition Bonds and Transition Loans have emerged as key instruments to channel capital toward companies and projects that are not yet "green," but are committed to aligning their activities with long-term climate objectives. These tools are designed primarily for *hard-to-abate* sectors—such as shipping, steel, aviation, and chemicals—where immediate compliance with green taxonomies is often technologically or economically unfeasible. The underlying principle is to support credible, science-based transition plans, allowing these sectors to progressively move toward carbon neutrality.

Specifically Transition Bonds are debt securities issued by corporates to finance or refinance activities that facilitate the transition toward a low-carbon economy[209]. Unlike green bonds—which require proceeds to be allocated strictly to environmentally eligible projects—transition bonds permit funding for activities that are not yet aligned with green standards but are expected to evolve over time. For instance, proceeds may be used to modernize high-emission assets, replace fossil-based inputs, or develop enabling infrastructure.

The structure of a transition bond generally includes use-of-proceeds requirements, along with clearly defined eligibility criteria that are rooted in a transition plan. This plan must demonstrate alignment with national or international climate targets (e.g., the Paris Agreement, net-zero by 2050), be time-bound, and incorporate sector-specific decarbonisation pathways. To maintain market credibility and avoid greenwashing, issuers are encouraged to obtain second-party opinions, follow robust disclosure standards, and commit to periodic reporting[210] As of today, transition bonds are based on the Transition Finance Handbook developed by ICMA[211] and by equivalent initiatives set out by the Climate Bonds Initiative (CBI)[212] standards and the EU Platform on Sustainable Finance's reports on transitional activities[213].

Transition Loans, in accordance with the Terms of Reference for the preparation of the Transition Loan Principles set out by the Loan Market Association[214], are expected to be structured as credit instruments provided by banks or syndicates to borrowers pursuing decarbonisation through investments that may fall outside the current EU Taxonomy eligibility. Unlike Sustainability-Linked Loans (SLLs), which are performance-based and can be used for general purposes, transition loans typically resemble green loans in that they involve ringfenced capital usage—but for assets or processes undergoing transformation rather than already being green. The key element in a transition

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[209] ICMA. (2023). *Climate Transition Finance Handbook*. International Capital Market Association.
[210] Climate Bonds Initiative. (2023). *Transition Finance Handbook*.
[211] https://www.icmagroup.org/sustainable-finance/sustainable-bonds-database/
[212] Climate Bonds Initiative. (2022). *Climate Bonds Standard and Certification Scheme*
[213] EU PSF. (2022). *EU Platform on Sustainable Finance: Final Report on the Social Taxonomy*. European Union.
[214] https://www.lma.eu.com/download?p=785503966-66178

loan is the presence of a credible transition strategy, validated internally and externally, that outlines how the borrower will evolve toward taxonomy-aligned activity. This may include retrofit of industrial equipment, fleet conversion plans, investments in circular manufacturing, or R&D in alternative fuels. Financial terms may include step-up clauses based on milestone achievement or target-based covenants related to emission intensity reduction, energy use or technology deployment.

Regulatory frameworks are evolving to support these instruments. The EU Platform on Sustainable Finance has provided high-level criteria for what constitutes "transition finance," including principles such as transparency, comparability, governance, and alignment with sectoral roadmaps[215]. The OECD[216] and the International Capital Market Association (ICMA)[217] have also published analytical frameworks to improve the integrity and scalability of transition finance solutions.

Both transition bonds and loans are designed to address a critical gap in sustainable finance: the need to finance the transformation of high-emission business models without prematurely excluding them from the capital markets. These instruments offer a pragmatic pathway toward decarbonisation, provided they are anchored in clear environmental objectives, embedded within corporate governance, and subject to rigorous reporting and verification.

For banks and investors, these tools offer new avenues to engage with clients on climate risk, integrate transition pathways into portfolio-level ESG metrics, and enhance alignment with prudential expectations under the European Central Bank (ECB) and European Banking Authority (EBA) supervisory frameworks.

2.4.1. Other sustainable finance instruments in the marine sector

In addition to Green Bonds and Loans, Sustainability-Linked Bonds (SLBs) and Sustainability-Linked Loans (SLLs), and Transition Loans and Bonds, Transition-linked Loans (TLLs) and Transition-linked Bonds (TLBs) there are several other sustainable finance instruments that are gaining relevance in the maritime sector and other high-emission sectors. The main ones are:

1. Blue Bonds: are financial instruments like Green Bonds but focused on the protection of marine ecosystems and the sustainability of ocean-related activities. They can finance

[215] EU Platform on Sustainable Finance. (2022). *Final Report on Minimum Safeguards and Transition Finance*.

[216] OECD. (2023). *A transition finance roadmap for climate action*. Organisation for Economic Co-operation and Development.

[217] International Capital Market Association (ICMA). (2021). *Climate transition finance handbook*.

initiatives such as reducing marine pollution, improving energy efficiency in shipping or building sustainable port infrastructure[218].

2. Social bonds: although mainly used for social objectives such as access to essential services or financial inclusion, they may be relevant in the maritime sector for projects related to improving seafarers' working conditions, safety on board or access to technologies to reduce pollution in port communities in accordance with the 2025 Social Loan Principles issued by the Loan Market Association[219].
3. ESG-Linked Loans: like Sustainability-Linked Loans, but with a broader structure that also includes social and governance parameters as well as environmental. They offer financial incentives to companies that improve their overall ESG practices, not just those related to decarbonization[220].
4. Blended Finance: a combination of public and private funds to fund sustainability projects. In the maritime sector, this tool can be used to reduce the risk of investment in new and not yet well-established technologies such as the use of ammonia or hydrogen as marine fuels

These additional tools offer innovative solutions to bridge the gap between traditional loans and bond instruments and the urgent need for decarbonization and sustainability, Transforming the maritime sector and other emissions-intensive industries through a combination of economic incentives and regulatory pressures that accelerate the ecological transition; In this context, sustainable finance is no longer just an option for companies that want to improve their ecological footprint, but a strategic necessity to remain competitive in a global market increasingly oriented towards innovation and sustainability, fundamental pillars of the future of the shipping and the global economy.

2.5. Connectivity criteria between ESG data and financial statement analysis: where KPIs are reflected in economic and financial data (CAPEX, OPEX, revenues, write-downs, depreciation)

The integration of ESG data into financial analysis is one of the main challenges and, at the same time, one of the strategic hubs in climate risk assessment and lending. In the banking context, the transition from "qualitative" sustainability to measurable sustainability that can be translated into balance sheet numbers implies a profound rethinking of valuation methodologies, risk pricing models

[218] International Finance Corporation. (2022). *Guidelines for blue finance: Guidance for financing the blue economy, building on the Green Bond Principles and the Green Loan Principles*. International Finance Corporation.
[219] Loan Market Association. (2025). *Social loan principles*.
[220] Imperial College Business School. (2024). *ESG-linked loans and sustainability-linked financing: Implications for corporate ESG strategies*. Imperial College London.

and performance metrics[221]. The key principle guiding this transformation is the translation of ESG Key Performance Indicators (KPIs) into traditional economic and financial items. This translation takes place through three levels of connection: operational, equity and income. This is a process that requires consistency between non-financial disclosure (CSRD, ESRS), sector data (e.g. Poseidon Principles) and financial reporting (statutory and consolidated IFRS financial statements)[222]

The progressive financialization of sustainability has forced a radical transformation in the way environmental, social and governance (ESG) factors are incorporated into credit decisions and financial metrics. Banks can no longer consider ESG data as ancillary or qualitative elements, but must integrate them into their risk assessment systems, particularly in the case of carbon-intensive sectors such as shipping. The principle of *connectivity* — i.e. the interconnection between financial reporting and sustainability reporting — aims to overcome the traditional fragmentation between these two information dimensions, creating a coherent and strategically oriented Annual Report. According to the framework proposed by EFRAG (2024[223]), *connectivity* makes it possible to understand how management choices deriving from risks, impacts and opportunities (IROs) translate into effects on the economic and financial performance of the company. The central question therefore becomes "how and where ESG KPIs are reflected in accounting and economic-financial quantities", and what are the mechanisms that allow their integration into internal banking processes.

2.5.1. Impact of ESG KPIs on CAPEX and OPEX: from strategy to cost structure

The first level of transmission takes place at the operational level and takes the form of the impact of ESG targets on investments and company costs. In a maritime enterprise, the decision to adopt cleaner technology — for example, a dual-fuel LNG/e-fuel engine, or a hybrid battery system — leads to an immediate increase in environmental CAPEX. These investments are recorded in the balance sheet in the form of tangible assets and are depreciated over a long-term horizon. Starting from EU Regulation 2020/852, companies must specify in their financial statements the share of CAPEX "taxonomy-aligned", i.e. allocated to activities compatible with European climate objectives[224]. For banks, this information is essential, because it allows them to objectively assess the company's

[221] European Central Bank. (2022). *Guide on climate-related and environmental risks*.
[222] IFRS Foundation. (2023). *IFRS Sustainability Disclosure Standards*.
[223] European Financial Reporting Advisory Group. (2024). *Connectivity considerations and boundaries of different Annual Report sections*. EFRAG Discussion Paper
[224] European Commission. (2020). *Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy).*

strategic orientation towards decarbonisation, and to classify it as a "green" or "transitory" activity in their ESG assets, with a direct impact on the Green Asset Ratio and credit allocation strategy[225].

In parallel, operating costs (OPEX) are also being modified by consistent ESG strategies. The switch to alternative fuels (e.g. bio-LNG, green methanol, e-fuel) involves an increase in the cost per ton compared to traditional fuel. This recurring increase in costs, although penalizing in the short term, reflects a reduction in the risk of regulatory transition and greater resilience of the business in the medium to long term. Banks must therefore update their cash-flow models at the level of individual counterparties to reflect this new cost structure, which should be read not as a sign of weakness, but as a lever of competitive differentiation[226]. In advanced internal models, CAPEX and OPEX ESG are included in the Net Present Value (NPV) adjuster, and their impact may affect financial covenants, the duration of the loan, or the acceptable leverage threshold[227].

2.5.2. ESG data and impacts on the income statement: revenues, impairment and accelerated depreciation and amortization

The second level of transmission is represented by the effects of ESG KPIs on the company's income profile, on revenues, write-downs and the amortization schedule. Companies that implement credible sustainability strategies can benefit from new business opportunities: access to green corridors, priority in low-emission ports, or contracts with large international shippers bound to ESG criteria[228]. These dynamics generate direct incremental revenues, which must be considered in the business plans subject to bank evaluation.

On the contrary, ships that do not comply with international environmental regulations (e.g. IMO 2023, EU maritime ETS from 2024) suffer a progressive deterioration of their use value[229]. This may lead to early impairment tests in accordance with IAS 36, triggered by a durable and foreseeable loss of economic value. For the bank, this results in a reduction in the collateral value of the ship collateral, which increases the Expected Credit Loss (ECL) under IFRS 9[230]

Not only that: the environmental deterioration of assets can lead to a revision of the residual useful life of the asset and, consequently, a shortening of the depreciation schedule. In practice, the ship will be considered economically obsolete before its physical decommissioning. This effect reduces

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225 European Central Bank. (2022). *Guide on climate-related and environmental risks*.

226 United Nations Environment Programme Finance Initiative (UNEP FI). (2021). *Rethinking Impact to Finance the SDGs*.

227 European Financial Reporting Advisory Group (EFRAG). (2023). *ESRS E1 – Climate Change*.

228 Poseidon Principles Association. (2023). *Annual Disclosure Report*.

229 European Commission. (2020). *Regulation (EU) 2020/852 on the establishment of a framework to facilitate sustainable investment (EU Taxonomy).*

230 IFRS Foundation. (2023). *IFRS Sustainability Disclosure Standards*.

forward EBITDA and worsens the bank's interest ratios, such as the DSCR (Debt Service Coverage Ratio), making the customer less bankable. Banks must therefore include in their models a risk function linked to the speed of environmental obsolescence, estimated based on the alignment of the asset with the IMO or EU decarbonisation curves[231]

2.5.3. Integration into internal models: how ESG data enters banking systems

The third level of connection is the systemic one: the direct integration of ESG data into internal banking risk and pricing models. ESG data, if standardized and verifiable (as required by the CSRD), can be transformed into quantitative variables within rating models, IRB models, ICAAP simulations and climate stress tests[232]. Banks classify counterparties based on their ESG profile (internal or assigned by data providers) and use this classification to modify probability of default (PD), loss in default (LGD) estimates and capital requirements.

In the maritime sector, for example, a bank can associate each ship financed with a "Climate Score" derived from the Poseidon Principles, which is then integrated into the risk management system to determine a capital multiplier. Ships with low environmental impact (emissions below the IMO benchmark) receive improved conditions on loan pricing and regulatory treatment; In contrast, carbon-intensive vessels require additional provisioning and may be subject to disengagement policies[233].

In addition, banks use climate predictive models developed jointly with entities such as NGFS and UNEP FI to estimate future exposure to climate shocks or forced transitions. These models include ESG metrics as structural inputs, as do financial data, and become an integral part of the institution's Risk Appetite Framework.

2.5.4. Obstacles and evolutionary perspectives: from data to system

Despite the growing attention, the systemic integration of transition-related KPIs into banking processes still faces numerous obstacles. First, the heterogeneity in the quality and structure of the data, especially for small and medium-sized enterprises not yet subject to the reporting obligations of the CSRD. This information asymmetry reduces the reliability of ESG assessments and increases the risk of greenwashing[234]. Second, many banks still do not have interoperable IT architectures between ESG systems, credit management and asset analysis. This prevents the construction of fully integrated

[231] European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD).*
[232] European Central Bank. (2022). *Guide on climate-related and environmental risks*.
[233] Poseidon Principles Association. (2023). *Annual Disclosure Report*.
[234] European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD).*

models and cross-checking between balance sheet data and non-financial KPIs. Third, in many cases there is a lack of a hybrid professional body (Transition-finance analysts) capable of correctly interpreting environmental indicators in the language of banking risk.

However, the mandatory introduction of ESRS standards, the strengthening of regulatory requirements (CRR III[235], SREP ESG[236]), and the development of data fusion technologies and artificial intelligence applied to climate risk, are quickly closing this gap. The goal, in the medium term, is to arrive at a system in which transition KPIs are automated in the banking workflow, weighted in decision-making models and tracked in portfolios, making sustainability a structural element in the assessment of creditworthiness and financial risk management.

2.5.5. Disconnects between financial reporting and sustainability reporting

The EFRAG paper (2024)[237] identifies several structural disconnections between the sections of the Annual Report, which compromise the consistency of information and hinder the integration of ESG data into decision-making processes, including banking processes. These disconnections manifest themselves on three levels: conceptual, methodological and operational.

Conceptually, ESG information is often treated as narrative and strategic, while financial accounting is based on quantitative metrics that are subject to rigorous standards (e.g. IFRS). This distinction creates an epistemic void between what is "material" for ESG impact and what is "relevant" for accounting purposes. The result is that many ESG risks or impacts known to the company are not considered in the statutory or consolidated financial statements, generating serious information asymmetries.

At a methodological level, ESG metrics are not explicitly linked to economic flows. For example, an ESG KPI such as the 20% reduction in annual emissions is not linked to the corresponding investment (CAPEX) reported in the financial statements. There are no *bridge tables* or reconciliation models between non-financial indicators and economic data (EFRAG, 2024, p. 12). The result is a disaggregated information system in which information cannot be used effectively in internal banking processes (e.g. ECL modeling, scenario analysis).

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[235] European Commission. (2021). *Regulation (EU) 2021/1423 of the European Parliament and of the Council on prudential requirements for credit institutions and investment firms (CRR III)*. Official Journal of the European Union.
[236] European Central Bank. (2022). *Guide on climate-related and environmental risks: Supervisory expectations relating to risk management and disclosure (SREP ESG)*. European Central Bank
[237] European Financial Reporting Advisory Group. (2024). *Connectivity considerations and boundaries of different Annual Report sections*. EFRAG Discussion Paper

At the operational level, the reporting boundaries are often divergent. Financial reporting is based on the criterion of financial control (IAS 27, IFRS 10), while ESG reporting often follows logics based on "significant influence" or on the "value chain" (Scope 3, upstream and downstream). This leads to situations where, for example, a material ESG risk to a joint venture or strategic supplier is excluded from the accounting section but included in the sustainability report, generating inconsistency (EFRAG, 2024, pp. 15–17).

2.5.6. Proposed solutions to improve connectivity

The EFRAG paper proposes a series of practical and conceptual tools to bridge the gap between financial and ESG reporting, improving connectivity both in terms of information content and report structuring.

1. Cross-referencing: consists of inserting hyperlinks, numerical references or direct references between sections. For example, a paragraph in the sustainability report that illustrates the reduction of emissions through a ship retrofit must explicitly indicate the corresponding CAPEX item in the financial statements. This allows users (analysts, banks, investors) to carry out a complete *tracing* between the environmental cause and the economic consequence (EFRAG, 2024, p. 22).
2. Bridge reporting/reconciliation tables: EFRAG recommends the use of *bridge tables* that show how ESG KPIs affect financial items (e.g. a table showing the impact of EU Taxonomy compliance on CAPEX, OPEX and asset value). This approach reflects the best practices already adopted by some multinationals and addresses the transition risk quantification needs required by banks in the ICAAP and SREP tests.
3. Alignment of the definitions of materiality: today financial materiality and sustainability materiality are separate ("double materiality" model). EFRAG suggests a convergence in an integrated approach, in which an event or factor is considered *material* if it has or will have measurable impacts on both dimensions (economic and environmental), introducing the concept of intertemporal materiality. This is crucial, for example, to identify a future impairment of an asset resulting from a climate risk that is not yet reflected in the accounts today (EFRAG, 2024, p. 27).
4. Integration of reporting calendars: EFRAG recommends the simultaneous publication of financial and ESG reports to avoid time mismatches, which generate inconsistency and loss of usefulness for stakeholders. This is crucial for banks, which need to perform timely counterparty assessments based on up-to-date and consistent data.

2.5.7. Operational and technical implications for banks and climate risk analysis

EFRAG's recommendations have structural impacts on banking processes in three areas: risk models, regulatory disclosures, and credit governance.

A. Banking modeling (IRB, IFRS 9, ICAAP):

To be used in IRB internal models, ESG data must be standardized, verifiable, and quantitatively reconcilable with balance sheet variables. Only through an integrated information system is it possible to use, for example, the taxonomy-aligned percentage of CAPEX as a factor to improve the ESG rating or to modulate the probability of default (PD) on a sectoral basis. This is particularly relevant for hard-to-abate sectors such as shipping, where models must assess the residual value of assets as a function of climate risk.

B. Regulatory disclosure (Pillar 3, EBA Guidelines, GAR):

Banks are required to provide regulatory climate indicators such as the Green Asset Ratio, the Banking Book Taxonomy Alignment Ratio (BTAR) and the KPI on financed emissions. Without *connectivity*, these indicators are affected by consolidation errors and misalignments between exposure and impact. Disconnects in reporting boundaries can cause a bank to misclassify an activity as taxonomy-aligned, when its environmental impact is outsourced.

C. Internal credit governance:

Full connectivity requires a review of credit granting processes. Forward-looking models must be able to simulate how an ESG risk (e.g. a rising carbon price) will affect future cash flows, the value of the asset pledged, and the sustainability of the business plan. In addition, due diligence processes must include traceability between environmental KPIs (Scope 1-2-3) and balance sheet items, also to avoid risks of greenwashing and regulatory sanctions (EFRAG, 2024, pp. 31–34).

Chapter 3 – Identification and classification of vessels and associated technologies

To effectively structure an assessment of the environmental and financial performance of the maritime sector, as well as to build reliable and comparable key performance indicators (KPIs), it is essential to start with a clear classification of ship types. This approach allows for a coherent analytical segmentation along three fundamental dimensions:

1. Substantial operational differences: each type of ship — whether it is a bulk carrier, oil tanker, container ship or LNG carrier — has unique operational characteristics (dimensions, routes, loads, average speed, duration of stops, fuel consumption, etc.) that directly influence both the emission profile and the possible decarbonization solutions. Each category of vessel, therefore, is designed to meet specific operational needs, which implies profound differences in terms of:
   - Operational profile: *container ships* are generally faster and operated on fixed routes (liner service), while *bulk carriers* and *tankers* are slower, with more flexible routes (tramp service). This directly affects the *average energy consumption per nautical mile*.
   - Dimensional and load characteristics: *deadweight tonnage (DWT), gross tonnage (GT)* and load capacity influence displacement, the type of propulsion needed and the possibility of using alternative solutions (such as rigid wing or wind-assist).
   - Usage patterns: some vessels operate on short-sea shipping routes, others on ocean routes. This results in different *energy profiles*, *electrification* or *battery* possibilities, and different storage requirements for alternative fuels such as ammonia or liquid hydrogen.
   - Load intensity and variability: for example, *LNG carriers* operate in cryogenic conditions and with complex on-board systems, while *RORO (roll-on/roll-off)* carriers have very dynamic load profiles. These aspects affect the selection of energy efficiency and exhaust gas treatment technologies.

Without a prior understanding of these variables, any analysis of emissions or technologies would be generic, inaccurate, and not applicable in the operational reality of fleets.

2. Technological diversification: the available and implementable technologies (alternative engines, propulsion systems, retrofits, low-carbon fuels, and energy efficiency technologies) are not universally applicable but must be evaluated in relation to the specific ship and its operational life cycle. Understanding the technological specificities linked to each category is therefore a prerequisite for estimating real impacts and transition costs. It is therefore essential, once the

vessels have been classified by type, to analyze the technologies available for the energy transition in a targeted and realistic way. The main differences lie in:

- Compatibility of technologies with the ship: not all solutions are *technology-ready* for all categories. For example:
    - *Hydrogen or methanol fuel cells* may be compatible with ferries or short-haul passenger ships, but not with VLCCs or ULCS for reasons of autonomy and storage space.
    - *Wind-assist technologies* are more suitable for bulk and general cargo than tankers.
- Technical and economic trade-offs: Some technologies, such as CO_2 capture (Carbon Capture and Storage on board) systems, involve structural *retrofitting* and high ancillary energy consumption, which can economically penalize small ships or ships with low operating margins.
- Different degrees of technological readiness (TRL): Fuel-switching technologies, such as the use of ammonia or green methanol, are in the experimental phase for some ships but already operational for others. The actual applicability depends strictly on the size and class of the ship.
- Category-specific regulations: Regulators such as the IMO and the EU often introduce differentiated technical requirements (e.g. MARPOL Annex VI, FuelEU Maritime), which apply differently depending on the type of vessel, port of call, type of cargo or route length.

For these reasons, the technological analysis must necessarily be conducted downstream of a clear segmentation by type of ship.

3. Carbon embedding and shipbuilding: only after identifying the type and technologies is it possible to correctly assess embodied carbon, i.e. the emissions incorporated in the construction and maintenance of ships (here we will only analyze Embedded Carbon Upstream in Ship Construction), as well as in the materials used. The assessment of the total carbon footprint (*Life Cycle Emissions*) and the construction or retrofit processes (*shipbuilding*) cannot be separated from the ship type, for three aspects:

- Embodied carbon: the emissions incorporated in the materials used (naval steel, paints, plants, treatment systems) vary greatly depending on the size and type of ship. A ULCC (Ultra Large Crude Carrier) can generate tens of thousands of tons of CO_2 already in the construction phase alone, while a scheduled ferry or an offshore support vessel has smaller but more frequent impacts due to the shorter life cycle.

- Modularity of construction: the possibility of retrofitting or repowering depends on the structure of the ship, the layout of the compartments and compatibility with new technological modules. Some ships are built with modular logic, others are not.
- Life cycle and economic depreciation: the expected lifespan of the ship and its residual value influence the convenience of investing in decarbonizing retrofits. An analysis that neglects the type of ship risks overestimating or underestimating the avoidable costs of emissions.

Starting from the classification of ships by type is an essential step to build a credible, technically based and financially assessable transition strategy. Only by accurately identifying the operational and structural characteristics of ships is it possible to: attribute effective KPIs for monitoring and reporting and support bank assessments consistent with ESG principles and international guidelines (Poseidon Principles, EU Taxonomy, CSRD).

In this chapter, we proceed with a systematic classification of the main types of ships used in global shipping, analyzing their technological characteristics relevant from the point of view of energy transition: from the type of fuel used to the average age of the fleet, from available retrofit options to the remaining useful life of the operating units with the aim of providing a framework that will allow, in subsequent chapters, to correctly associate key performance indicators (KPIs) and financial risk metrics compatible with the decarbonization of the sector. Particular attention will be paid to key technologies (such as scrubbers, reciprocating engines, digital twins, hybrid propulsion systems) and embedded carbon analysis as a critical parameter in the integrated assessment of environmental footprint and return on sustainable investments.

3.1. Classification of the main types of ships

The global fleet consists of a wide range of ship types; each designed for specific logistical and operational functions. For a correct assessment of the transition potential to alternative fuels and low-carbon technologies, it is essential to start from a clear classification of the main categories of vessels, considering their structural and functional peculiarities. The most relevant classes of ships from a commercial and environmental perspective are listed below:

1. Container Ships: Container ships are one of the most common vessel types in shipping. A container ship is a type of merchant vessel specifically designed for the transportation of standardized containers (ISO 668[238]), which form the backbone of international trade and global logistics. These

[238] https://www.iso.org/obp/ui/en/#iso:std:iso:668:ed-7:v1:en

ships have an open-deck structure without covers between the holds, facilitating loading and unloading operations. Inside the holds, guide cells ensure proper alignment and stability of the containers during transport. Some container ships are equipped with integrated cranes, while others rely on port infrastructure for handling operations.
The cargo capacity of a container ship is measured in TEU (Twenty-foot Equivalent Unit), which represents the number of 20-foot (6.1-meter) containers it can carry. Container ships are classified based on their size and capacity: Feeder vessels, with a capacity of up to 3,000 TEU, are used for local or regional transport; Panamax ships, capable of carrying up to 5,000 TEU, are designed to pass through the Panama Canal; Post-Panamax vessels, with capacities ranging from 5,000 to 10,000 TEU, are too large for the old Panama Canal; finally, Ultra Large Container Ships (ULCS), with over 18,000 TEU, operate on intercontinental routes such as those between Asia and Europe. From a technical perspective, these ships primarily use low-speed, two-stroke diesel engines optimized for fuel efficiency and operational effectiveness. In recent years, the shipping industry has invested in emission-reduction technologies, adopting systems such as scrubbers to cut sulfur oxides (SOx) and experimenting with alternative fuels like liquefied natural gas (LNG)[239]. Container ships operate on fixed routes and are part of strategic alliances between shipping companies to optimize costs and maximize cargo capacity. Major transit ports include Shanghai, Singapore, Rotterdam, Los Angeles, and Dubai, which serve as key hubs in global trade. These vessels are the backbone of international commerce, transporting over 80% of the world's goods. The introduction of containerization has revolutionized logistics by making maritime transport faster, safer, and more cost-effective, reducing shipping expenses and fostering market globalization. Ekmekçioğlu et al. (2021).[240]

2. Bulk Carriers: A bulk carrier is a type of merchant vessel specifically designed to transport large quantities of unpackaged bulk cargo such as grains, coal, iron ore, cement, bauxite, and fertilizers. These ships are fundamental to global trade, particularly for industries like agriculture, mining, and construction. Their structure is designed for efficiency, with large cargo holds that facilitate the loading and unloading of materials. Equipped with hatch covers to protect the cargo from weather conditions, some bulk carriers have onboard cranes, making them self-sufficient for cargo handling,

[239] Ekmekçioğlu, A., Ünlügençoğlu, K., & Çelebi, U. B. (2021). Estimation of shipping emissions based on real-time data with different methods: A case study of an oceangoing container ship. *Environment, Development and Sustainability, 23*(9), 13577–13613.
[240] Ekmekçioğlu, A., Ünlügençoğlu, K., & Çelebi, U. B. (2021). *Estimation of shipping emissions based on real-time data with different methods: A case study of an oceangoing container ship*. *Environment, Development and Sustainability*.

while others rely on port infrastructure. The hull is reinforced to withstand the stress generated by carrying dense materials like iron ore or coal.

Bulk carriers are classified based on their size and cargo capacity, measured in deadweight tonnage (DWT), which represents the ship's total carrying capacity, including cargo, fuel, and provisions. Smaller vessels such as Handysize bulk carriers, ranging from 10,000 to 40,000 DWT, are ideal for smaller ports with limited infrastructure, often transporting grains or fertilizers. Handymax and Supramax vessels, with a capacity between 40,000 and 60,000 DWT, are more versatile, often equipped with onboard cranes for independent loading and unloading. Panamax bulk carriers, designed to fit through the old Panama Canal, typically range from 60,000 to 80,000 DWT and are used primarily for coal and grain transport. Post-Panamax ships, which exceed the dimensions of the original Panama Canal but can operate on major global trade routes, range from 80,000 to 120,000 DWT. Larger vessels, such as Capesize bulk carriers, with a capacity exceeding 120,000 DWT, are too large for the Panama and Suez Canals and must navigate around Cape Horn or the Cape of Good Hope. The largest category includes Very Large Ore Carriers (VLOCs), exceeding 200,000 DWT, primarily used for iron ore trade between regions such as Brazil and China.

Bulk carriers are typically powered by low-speed, two-stroke diesel engines optimized for long voyages and fuel efficiency. Recent technological advancements have focused on improving energy efficiency through hull modifications, slow steaming strategies, and the use of alternative fuels such as liquefied natural gas (LNG). Unlike container ships that follow fixed schedules, bulk carriers generally operate on a tramp shipping model, meaning they do not adhere to regular routes but instead navigate based on market demand and cargo availability. The loading and unloading process can take several days, depending on the type of cargo and port infrastructure. Playing a crucial role in the global economy, bulk carriers transport approximately 40% of the world's total cargo volume[241], enabling the movement of raw materials essential for steel production, agriculture, and energy sectors. The growing demand for bulk commodities, particularly from emerging markets in Asia, has led to an increased reliance on these vessels for transporting iron ore, coal, and grain across long distances. Their efficiency and capacity make them indispensable to the functioning of global trade and industrial supply chains. (Achmadi et al., 2023).[242]

[241] Sandberg, A. (2024). *Towards sustainable shipping: Development in CII performance of a Bulk Carrier* [bachelor's thesis, Arcada University of Applied Sciences]. Deltamarin.
[242] Achmadi, I., Kurniawan, A., & Rahman, A. (2023). *Energy efficiency and emission reduction strategies for bulk carriers: A review of technological and operational approaches*. *Ocean Engineering, 271*, 113251.

3. Tanker Ships: A tanker ship is a type of merchant vessel specifically designed for the transportation of bulk liquids, such as crude oil, petroleum products, chemicals, liquefied natural gas (LNG), and food-grade liquids like vegetable oils or wine. These ships play a crucial role in global maritime trade, facilitating the movement of vast quantities of energy resources and essential raw materials for industries and everyday consumption. Tanker ships are characterized by their internal structure, which consists of multiple storage tanks, separated by bulkheads to allow the transport of different liquid cargoes without contamination. They are equipped with advanced pumping systems for loading and unloading, which takes place through specialized pipelines. Some tankers also feature heating systems to maintain the viscosity of certain liquids, such as heavy crude oil.

Depending on the type of cargo transported, tanker ships are divided into several categories. Oil tankers, which transport crude oil and petroleum products, are further classified by size. Aframax tankers (80,000-120,000 DWT) are commonly used for regional trade, while Suezmax tankers (120,000-200,000 DWT) are designed to pass through the Suez Canal at full capacity. The Very Large Crude Carriers (VLCC), with capacities ranging from 200,000 to 320,000 DWT, and Ultra Large Crude Carriers (ULCC), exceeding 320,000 DWT, operate on intercontinental routes connecting major oil hubs in the Middle East and Asia. Another important category includes chemical tankers, specialized in carrying hazardous liquid chemicals such as acids and solvents. These ships are constructed with tanks lined with special materials, such as stainless steel or epoxy coatings, to prevent chemical reactions with the cargo. LNG carriers are designed to transport liquefied natural gas at extremely low temperatures (-162°C) and feature cryogenically insulated storage tanks. Similarly, LPG carriers transport liquefied petroleum gas (such as propane and butane), requiring pressurized or refrigerated storage.

From an operational perspective, tanker ships must comply with strict environmental and safety regulations, as accidents such as oil spills or chemical leaks can have severe ecological consequences. In recent years, the maritime industry has implemented measures to reduce emissions and improve energy efficiency, including the use of low-sulfur fuels and exhaust gas cleaning systems (scruffers). Tanker ships are essential to the global supply chain for energy and liquid raw materials. Their ability to transport vast amounts of cargo over long distances connects major production centers with consumer markets, ensuring the continuity of international trade and the stability of energy and industrial sectors. (Gnip & Velkavrh, 2022).[243]

[243] Gnip, P., & Velkavrh, M. (2022). *The impact of emission control areas (ECAs) on tanker ship propulsion and fuel consumption. Transportation Research Part D: Transport and Environment, 102*, 103129.

4. Fishing Vessels: A fishing vessel is a type of ship specifically designed for the capture, storage, and transportation of fish and other marine resources. These vessels vary significantly in size, structure, and equipment depending on the type of fishing they are intended for and the environments in which they operate, ranging from coastal waters to deep-sea fishing grounds.

Structurally, fishing vessels are built with reinforced hulls to withstand the often-harsh marine conditions, especially for offshore and deep-sea operations. Their lengths can range from a few meters, in the case of small artisanal boats, to over 100 meters for industrial fishing ships or factory trawlers. Onboard, these vessels feature large storage areas, often equipped with refrigeration or rapid freezing systems to preserve the freshness of the catch. The onboard equipment varies depending on the fishing method used. Trawlers are fitted with powerful winches and pulley systems to deploy and retrieve heavy nets from the seabed. Longliners use extensive lines with thousands of baited hooks, along with automated systems for setting and retrieving them. Purse seiners have specialized gear for surrounding and capturing entire schools of fish, while tuna fishing vessels are equipped with radar, sonar, and even drones to locate tuna schools efficiently. A crucial feature of industrial fishing vessels is the presence of processing facilities onboard, particularly on freezer trawlers and factory ships, where fish are immediately gutted, processed, and frozen in refrigerated storage compartments. Some of these large vessels even have onboard facilities for producing fish meal and fish oil, transforming them into floating processing plants. In terms of propulsion, fishing vessels are typically powered by medium- to high-powered diesel engines, designed to ensure long-range autonomy and endurance in extreme ocean conditions. Smaller boats may use inboard or outboard engines, depending on their operational needs. Many of these vessels also incorporate stabilizers or specialized keels to reduce rolling during navigation and fishing operations, improving crew safety and fishing efficiency. Modern fishing vessels must comply with international safety and sustainability standards. They are often equipped with Vessel Monitoring Systems (VMS), which allow authorities to track their movements and ensure compliance with fishing regulations. The International Maritime Organization (IMO) and the Food and Agriculture Organization (FAO) set guidelines for vessel tracking and the use of fishing gear that minimizes bycatch (the unintended capture of non-target species). With advanced technology and specialized capabilities, fishing vessels are among the most highly specialized segments of the global merchant fleet, ensuring the supply of seafood products to the global market. However, the industry faces growing challenges related to sustainability, overfishing, and reducing the environmental impact of industrial fishing, highlighting the need for continued innovation and responsible fishing practices. (Zhang et al., 2020).[244]

5. Ro-Ro Passenger Ships: A Ro-Ro Passenger Ship is a type of vessel designed to transport both wheeled vehicles (such as cars, trucks, buses, and trailers) and passengers. The term Ro-Ro stands for *Roll-on/Roll-off*, meaning that vehicles can embark and disembark autonomously using built-in ramps, without the need for cranes or lifting equipment.

Structurally, Ro-Ro passenger ships combine the features of a ferry with those of a cargo vessel, providing space for vehicles alongside accommodations and public areas for passengers. These ships have large cargo decks divided into multiple levels, equipped with securing systems to keep vehicles stable during navigation. The access ramps, located at the stern, bow, or sides, allow for fast loading and unloading at equipped ports. The size and capacity of Ro-Ro passenger ships vary depending on their intended use. Ro-Pax ferries operate on short routes, such as island connections or crossings of maritime straits, and can carry a few hundred vehicles and passengers. Cruise Ro-Ro ships, on the other hand, are designed for long international routes and offer comfortable accommodations, including restaurants, private cabins, shopping areas, and recreational spaces. In terms of propulsion, Ro-Ro passenger ships use medium- to high-powered diesel engines, designed to ensure stable speeds while optimizing fuel consumption. Many newer models incorporate emission reduction technologies, such as scrambers to limit sulfur oxides (SOx) and liquefied natural gas (LNG) propulsion systems for greater energy efficiency. (Gnip & Velkavrh, 2022).[245]

6. General Cargo Ships: General Cargo Ships are a type of merchant vessel designed for transporting non-containerized and non-liquid cargo. These ships are highly versatile and are used to carry a wide variety of goods, including machinery, construction materials, timber, steel, automobiles, packaged food products, and palletized cargo.

Structurally, general cargo ships are characterized by large cargo holds and a reinforced main deck, allowing for the transport of bulky or heavy loads. Unlike container ships, general cargo vessels are often equipped with onboard cranes and winches, enabling them to load and unload cargo even in ports with limited infrastructure. Some modern vessels in this category feature multiple decks or partitioned cargo holds, allowing for the simultaneous transportation of different types of goods.

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[244] Zhang, Y., Xu, X., & Li, J. (2020). *Sustainability and energy efficiency in fishing vessel operations: Advances and challenges*. *Journal of Marine Science and Engineering, 8*(9), 695.

[245] Gnip, P., & Velkavrh, M. (2022). *Evaluation of Ro-Ro passenger ship emissions and strategies for reducing environmental impact*. *Sustainable Transport Review, 7*(3), 276–290.

General cargo ships can be classified into different types based on their operational characteristics. Multipurpose vessels (MPP) are among the most common and can carry both bulk and palletized cargo, containers, or heavy loads. Breakbulk ships specialize in transporting oversized or heavy cargo that cannot be containerized, such as large industrial components or infrastructure equipment. Some vessels in this category are also equipped with climate-controlled holds, allowing the transport of sensitive goods such as food products or pharmaceuticals.
From a propulsion perspective, general cargo ships use medium-powered diesel engines, optimized for fuel efficiency over medium- and long-distance voyages. Since they often operate on flexible and non-fixed routes, they must be adaptable to different cargo conditions and adjust their speed according to transport requirements. In terms of commercial operations, general cargo ships do not follow fixed schedules like container ships but instead operate under a tramp shipping model, navigating to destinations as required by market demand. This flexibility makes them a vital asset for transporting specialized goods or supplying markets with fluctuating demand. (Achmadi et al., 2023).[246]

7. Passenger Ships: Passenger ships are vessels designed for the transportation of people, whether for scheduled routes or for tourism and recreational purposes. These ships vary significantly in size, capacity, and onboard amenities, ranging from small local ferries to large luxury cruise ships. They are designed to ensure comfort, safety, and stability, incorporating advanced navigation and propulsion systems. Passenger ships are categorized based on their function. Ferries operate on short-distance routes, such as island connections or maritime strait crossings, and may carry both passengers and vehicles (Ro-Pax). Cruise ships are designed for tourism and offer a wide range of luxury services, with itineraries lasting from a few days to several weeks. Expedition ships are smaller and specialized for travel to remote areas, such as Antarctica or the Arctic, providing immersive nature experiences. In terms of propulsion, passenger ships typically use diesel or hybrid engines, with a growing focus on energy efficiency and emission reduction. Many modern vessels adopt environmentally friendly fuels, such as liquefied natural gas (LNG), to minimize their ecological impact. (Greig et al., 2020).[247]

Understanding the emissions and environmental impacts of these main types of shipping vessels is crucial for developing strategies to reduce carbon emissions, improve fuel efficiency, and mitigate the environmental footprint of maritime transportation. Aiming to simplify the analysis, we have

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246 Achmadi, I., Kurniawan, A., & Rahman, A. (2023). *Operational efficiency and environmental impact of general cargo ships: A systematic review*. *Maritime Policy & Management, 50*(2), 289–306.
247 Greig, R. A., Smith, B. J., & Taylor, M. P. (2020). *Energy consumption and sustainability measures in passenger ships: Future perspectives*. *Journal of Cleaner Production, 258*, 120689.

grouped the different types of ships into seven main categories, without going into detail about each specific variant. This approach provides a clear and effective overview of the main operational, structural, and economic characteristics of each ship type.

3.2. Relevant technology and operational characteristics for transition assessment.

Assessing the energy and environmental transition in the shipping sector requires a detailed analysis of the intrinsic characteristics of individual vessels, as these significantly influence both the decarbonization potential and the technical and economic feasibility of adopting alternative technologies. In this context, each ship must be understood as a complex system whose structural, mechanical, and operational conditions directly shape its ability to align with international decarbonization targets, particularly those established by the IMO and the European Union.

Among the most relevant parameters in this evaluation is the year of construction, which serves as a synthetic indicator of the vessel's technological generation. It reflects the regulatory, design, and industrial environment in which the ship was built and thus influences its emissions profile, compliance with current standards, and predisposition to retrofitting. For example, ships built before the introduction of the Energy Efficiency Design Index (EEDI) in 2013 generally exhibit lower energy performance and are less compatible with alternative fuels without significant structural modification.

Closely linked to the year of construction is the type of fuel used, which directly determines the vessel's emissions of greenhouse gases and air pollutants. Ships powered by Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO) produce high levels of CO_2, sulfur oxides (SOx), and nitrogen oxides (NOx), and are among the main contributors to the sector's environmental impact. Transitioning to cleaner fuels—such as Liquefied Natural Gas (LNG), green methanol, or ammonia—is a possible solution, though it often requires specific onboard systems and onshore infrastructure that are not available on most existing vessels[248].

Another key parameter is the availability of retrofit options, meaning the set of technical interventions that can be applied to existing ships to improve their environmental performance. These include the installation of scrubbers for SOx removal, conversion to alternative fuels, hull and propeller optimization, and the integration of digital systems for smart navigation and load management.

[248] Karatug, C., Ceylan, B. O., Ejder, E., & Arslanoglu, Y. (2023). *Investigation and examination of LNG, methanol, and ammonia usage on marine vessels*. Maritime Faculty, Karadeniz Technical University, Turkey.

However, the feasibility of such upgrades depends on the vessel's technical configuration, its age, and the expected return on investment.

The lifespan of the vessel is another strategic factor, generally ranging between 20 and 30 years but heavily influenced by the vessel's operational profile, maintenance history, and economic performance. Ships nearing the end of their economic life are often excluded from modernization programs, as the associated investments would not be recoverable. Conversely, relatively recent ships that are not yet compliant with environmental standards often become prime candidates for targeted retrofitting.

Lastly, it is essential to consider a range of additional technical and operational factors, such as the type and power of the installed engine, cruising speed, hull hydrodynamics, onboard automation systems, type of trade route (oceanic vs. short-sea shipping), and port call frequency. All these elements contribute, directly or indirectly, to a vessel's environmental impact and its capacity for transition. The interaction among these variables defines the overall degree of alignment between the ship and future decarbonization scenarios, as well as its attractiveness in the context of global sustainable finance initiatives.

3.2.1. Year of Construction

The year a ship is built is a crucial indicator for assessing its potential for ecological and technological transition. It determines not only the vessel's original energy efficiency but also its compliance with international environmental regulations in force at the time of design and its structural flexibility for adopting more sustainable technologies. Generally, the more recent a ship is, the greater the likelihood that it meets IMO requirements and is structurally and digitally prepared for conversion to alternative fuels or low-emission propulsion systems.

Since the 2000s, the International Maritime Organization (IMO) has introduced a series of regulatory reforms, significantly accelerating them from 2013 onward. Ships built before this date are generally exempt from any design constraint aimed at reducing greenhouse gas emissions, as they are not subject to the so-called Energy Efficiency Design Index (EEDI). These ships are typically designed according to outdated industrial and energy standards, often powered by high-sulphur fuels and equipped with low-efficiency engines. As a result, they not only consume more fuel but are also more difficult to upgrade to comply with new environmental regulations due to the lack of technical space and onboard configurations needed for installing scrubbers or adapting to alternative fuels.

From January 1st, 2013, with the entry into force of the EEDI, new builds have been required to meet minimum energy efficiency standards based on CO_2 emissions per ton per nautical mile. This regulatory step marked a significant qualitative leap in ship design, pushing shipyards to invest in more hydrodynamic hulls, more efficient engines, and onboard technologies geared toward consumption monitoring[249]. Even more significant is the threshold of January 1st, 2023, when the IMO introduced two key regulatory instruments: the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI). The former measures a ship's annual carbon intensity performance, while the latter imposes efficiency standards even on existing vessels, sometimes requiring speed reductions or retrofits to avoid penalties in environmental classification[250].

From a technological standpoint, the year of construction is closely linked to the feasibility of retrofitting interventions. Ships built before 2000 often feature outdated engines, analogy electrical systems, rigid internal compartmentalization, and no provision for advanced onboard technologies. In such cases, operations like fuel system replacement, scrubber installation, or digital optimization system integration become highly expensive and technically challenging. In contrast, ships built after 2013 are partially optimized for energy efficiency and often include modular structures or technical layouts that facilitate conversion to LNG, methanol, or other low-emission alternatives. Lastly, vessels constructed after 2020 are often designed to be "fuel-ready," meaning compatible with multiple alternative fuels, and equipped with integrated automation systems, digital twins, environmental sensors, and hybrid architectures[251]. The average age of the global fleet also varies considerably depending on the ship type. Bulk carriers and oil tankers, for instance, have an average age between 10 and 12 years[252]—a range that, with proper maintenance, still allows for targeted sustainability interventions. Container ships, although of similar age, require more frequent overhauls due to intensive operational use. LNG carriers are typically the youngest category in the fleet, with an average age of 7–9 years, and are already prepared for advanced propulsion systems. On the other hand, passenger and ro-ro vessels tend to be older and less efficient, making sustainable retrofitting both technically and financially challenging[253]. The year of construction also affects other key aspects of the transition assessment. It directly influences the default fuel system onboard, the level of automation and digitalization, the remaining economic life of the ship, and consequently, its attractiveness for new investments. Financial and insurance institutions—ever more guided by ESG

[249] BOTTOM. (2013). *Improving the energy efficiency of ships*
[250] BOTTOM. (2023a). *Rules on ship, carbon intensity and rating system enter into force*.
[251] DNV. (2023). *EEXI and CII - ship carbon intensity and rating system*.
[252] Sandberg, A. (2024). *Towards sustainable shipping: Development in CII performance of a Bulk Carrier* [bachelor's thesis, Arcada University of Applied Sciences]. Deltamarin.
[253] Clarksons. (2023). *EEXI CII Regulation*.

principles—tend to view older ships as potential stranded assets, meaning vessels likely to lose value before the end of their economic life due to non-compliance with environmental standards[254].
In conclusion, the year of construction stands out as a synthetic and strategic variable. It allows for an informed evaluation of a ship's compatibility with the decarbonization goals of the maritime sector, the financial and technical sustainability of necessary upgrades, and the investment risk tied to its future presence on the market.

3.2.2. Fuel Type

The type of fuel used by a ship is one of the most determining factors for its environmental impact and positioning itself with respect to the decarbonization objectives of the maritime sector. It directly affects the emission levels of carbon dioxide (CO_2), sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter, affecting not only compliance with current and future environmental regulations, but also the technical complexity and economic sustainability of the transition to cleaner operating solutions[255].
Historically, most of the world's merchant fleet has relied on Heavy Fuel Oil (HFO) or Intermediate Fuel Oil (IFO), fuels characterized by a high sulphur content and a strong impact in terms of air pollution. These fuels are cheap and widely available, but they are among the most carbon-intensive energy sources in shipping. The International Maritime Organization (IMO), through regulations such as MARPOL Annex VI, has introduced increasingly stringent limits on the sulphur content of marine fuels, culminating in the global limit of 0.5% that came into force in January 2020[256]. To meet this threshold, shipowners have been forced to switch to alternative fuels with a low sulphur content or to install fume abatement systems (*scrubbers*).
One of the most popular alternatives is Low Sulphur Fuel Oil (LSFO), which meets the limits on sulphur content but continues to rely on the combustion of fossil fuels and therefore generate significant amounts of CO_2. Similarly, fuels such as Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) offer more efficient combustion and particulate matter reduction, but they are still fossil fuels and do not represent a long-term solution for the full decarbonization of the sector[257].
In recent years, the shipping industry has turned increasing attention to Liquefied Natural Gas (LNG) as a transition fuel. Liquefied Natural Gas (LNG) is currently the most popular alternative fuel in the shipping industry globally. Considered a transition fuel, it allows a significant reduction in polluting

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[254] BOTTOM. (2023b). *EEXI and CII - ship carbon intensity and rating system*.
[255] DNV. (2023a). *LNG as Ship Fuel – Position Paper*
[256] BOTTOM. (2020a). *Sulphur 2020 – IMO Regulation*
[257] EMSA. (2022). *The European Maritime Transport Environmental Report 2022*. European Maritime Safety Agency

emissions compared to traditional fuels, while remaining a fossil derivative. Composed mainly of methane, LNG is liquefied by cooling to about -162 °C, reducing its volume by about 600 times and making it easier to store and transport on board[258]. From an environmental point of view, the use of LNG allows the almost total reduction of sulphur oxide (SO_x) emissions, a reduction of between 70 and 85% of nitrogen oxide (NO_x) emissions and the almost complete elimination of particulate matter, while ensuring a reduction in CO_2 emissions of 20-25% compared to marine diesel, at least if the combustion phase (*tank-to-wake*)[259] is considered. However, if we consider the entire life cycle (*well-to-wake*), the carbon balance of LNG can worsen due to the so-called *methane slip*, i.e. the release of unburned methane into the atmosphere during use and management, a problematic phenomenon as methane is a greenhouse gas with a climate-changing potential much higher than that of CO_2[260]. The use of LNG offers several technical advantages: dual-fuel engines, developed by companies such as MAN Energy Solutions and Wärtsilä, allow both LNG and traditional liquid fuels to be used, offering operational flexibility and greater resilience in the event of supply shortages[261]. Cleaner combustion at lower temperatures compared to conventional fuels reduces wear and tear on mechanical components and the need for maintenance, while the absence of sulphur and the non-corrosiveness of LNG contribute to a greater durability of propulsion systems. Globally, recent years have seen a significant expansion of the LNG bunkering network, with the construction of terminals in strategic ports and the entry into service of tankers dedicated to refuelling, encouraging the adoption of LNG in segments such as containers, cruises, ferries and car carriers[262]. However, LNG also presents important structural and operational challenges. The need to keep it in a liquid state requires the adoption of complex cryogenic systems, with thermally insulated tanks, often *of the membrane* or *Moss* type, which take up more space and reduce the ship's payload capacity[263]. In addition, it is essential to control the phenomenon of *boil-off gas*, i.e. the natural evaporation of LNG, which requires evaporated gas recovery and management systems. LNG-powered ships must also comply with the safety standards set by the IGF Code[264], which impose strict requirements on space separation, forced ventilation, fire suppression systems and leak detection sensors. From an energy point of view, LNG has a lower calorific value than conventional fuels per unit volume, while having a competitive energy content per unit mass, which entails the need to design larger tanks to ensure

[258] DNV. (2023b). *Methanol as Marine Fuel – Technical Update*
[259] Clarksons. (2023). *Green Transition: LNG-Fueled Fleet Development*.
[260] European Commission. (2021). *EU Strategy to Reduce Methane Emissions*.
[261] Wärtsilä. (2022). *Dual-Fuel Engines for Marine Applications*.
[262] Clarksons. (2023). *Green Transition: LNG-Fueled Fleet Development*.
[263] ABS. (2021). *LNG Bunkering: Technical and Operational Advisory*. American Bureau of Shipping.
[264] BOTTOM. (2020b). *IGF Code – Safety for Ships Using Low-Flashpoint Fuels*.

the same operating autonomy. In addition, the fossil character of LNG limits its compatibility with the long-term decarbonization goals set by the IMO and the European Union. To remain a sustainable solution in the future, LNG will need to progressively evolve towards low or net-zero emission forms, such as bio-LNG produced from liquefied biogas or e-LNG synthetically obtained from green hydrogen and captured CO_2. However, these technologies are still in the experimental phase and are characterized by high costs and limited availability. Therefore, although LNG today represents one of the most technically mature and widespread options for reducing emissions in the shipping sector, its long-term sustainability will depend on the ability of the market and institutions to invest in a truly carbon-neutral supply chain. The long-term outlook focuses on next-generation fuels, such as biofuels, green methanol, ammonia and hydrogen, each with specific benefits and challenges.

Biofuels are liquid fuels derived from bio-based feedstocks (biomass), such as vegetable oils, animal fats, organic waste, or dedicated crops[265]. The second and third generation ones (e.g. HVO – Hydrotreated Vegetable Oil, FAME – Fatty Acid Methyl Esters, or bio-oil from algae) are particularly suitable for the maritime sector due to their compatibility with existing ship engines (*drop-in fuels*).[266] This means that, with minimal modifications to the systems, they can be used as a replacement for conventional fuels.

From a technical point of view, biofuels have a lower calorific value than marine diesel (about 36–39 MJ/kg compared to 42–45 MJ/kg for fossil fuels) but offer the advantage of very low net CO_2 emissions, as the CO_2 emitted in combustion is largely reabsorbed in the biomass growth cycle from which they derive[267]. However, the oxygen content and hygroscopic properties of some biofuels can lead to corrosion problems, long-term instability, and clogging of filters, necessitating careful management of operating conditions.

Green methanol is a simple alcohol (CH_3OH) produced through the combination of green hydrogen (obtained by electrolysis from renewable sources) and CO_2 captured by industrial or atmospheric processes[268]. The molecule is liquid at room temperature, easily pumped, and safer to handle than other alternative fuels, while being toxic by ingestion and inhalation. From an engineering point of view, methanol can be used in internal combustion engines with relatively limited modifications, thanks to its high miscibility with water, good vaporization capacity, and absence of particulate matter in combustion. However, it has a much lower calorific value than conventional fuels: about 19.7

[265] International Chamber of Shipping. (2021). *A zero emission blueprint for shipping* (in collaboration with Ricardo). International Chamber of Shipping.
[266] Lloyd's Register. (2021). *Biofuels in Shipping: A Strategic Outlook*
[267] International Renewable Energy Agency (IRENA). (2021). *Innovation outlook: Renewable methanol.*
[268] International Renewable Energy Agency (IRENA). (2021). *Innovation outlook: Renewable methanol.*

MJ/kg compared to 42–45 MJ/kg for marine diesel[269]. This involves the need for larger volume tanks or more frequent bunkering to ensure the same autonomy. Its adoption is facilitated by the increasing availability of dual-fuel methanol/diesel engines by OEMs such as MAN Energy Solutions and Wärtsilä, and some large players (e.g., Maersk) are already investing in new methanol-ready builds.

Ammonia (NH_3) is a zero-carbon fuel, ideally produced by the Haber-Bosch process powered by green hydrogen. It is a highly water-soluble gas, liquefiable at moderate pressures and transportable in liquid form at about –33 °C. Its main advantage is the absence of CO_2 during combustion, making it one of the most attractive options in terms of full decarbonization[270]. However, from a technical point of view, ammonia presents considerable criticalities. First, it has a very low calorific value (about 18.6 MJ/kg), which makes it less energy-efficient than other fuels. It also has a narrow flammability window, a slow burn rate, and a tendency to generate high NO_x, making it difficult to design efficient and safe engines. It is also extremely toxic, posing high risks to the health of the crew in the event of accidental leaks or spills. For this reason, its large-scale deployment requires the adoption of advanced containment, ventilation, detection and neutralization systems, as well as rigorous training protocols for cabin crew[271].

Hydrogen (H_2) is the energy carrier with the highest energy content per unit mass (about 120 MJ/kg), but it presents great difficulties related to the energy density per unit volume, which is extremely low. For naval use, it can be used in cryogenic liquid form (at –253 °C), compressed at high pressure (350–700 bar), or through chemical carriers (e.g. ammonia or methanol itself). It can be used in modified combustion engines, but is particularly promising in combination with fuel cells, which enable combustion-free electrochemical energy conversion with zero direct emissions[272].

The main technical challenges are related to cryogenic storage and handling, material compatibility (hydrogen tends to cause *embrittlement*, i.e. brittleness in metals) and the risk of detonation in the presence of leaks. In addition, the green hydrogen supply chain is still in its infancy, with high costs, low availability and the absence of a port network for industrial-scale bunkering. However, in short-sea shipping or short-haul routes, hydrogen could be one of the most promising solutions, especially in the medium to long term[273].

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[269] DNV. (2023b). *Methanol as Marine Fuel – Technical Update*.
[270] ABS. (2022). *Ammonia as Marine Fuel: Risk and Regulatory Issues*. American Bureau of Shipping.
[271] Ricardo Energy & Environment. (2022). *Ammonia environmental impact study*. Maritime Decarbonisation Hub.
[272] IEA. (2022). *Hydrogen in Shipping: Towards Decarbonisation*. International Energy Agency.
[273] International Renewable Energy Agency (IRENA). (2022). *Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and Way Forward*.

Fuel	Origin	CO_2 (tank-to-wake)	SOx/NOx/PM	Calorific value (MJ/kg)	Available technology	Key challenges
HFO	Fossil	High	High	40-45	Widespread	High environmental impact
LSFO	Fossil	High	Low	42-44	Widespread	Fossil anchor
MDO/MGO	Fossil	High	Low	43-45	Widespread	Fossil anchor
LNG	Fossil	Medium (-20/25%)	Very low	50 (but low density)	Diffused (dual-fuel)	Methane briefs, cryogenics
Biofuels	Biomass (2nd/3rd Jan)	Very low	Low	36–39	Compatible (drop-in)	Stability and corrosion
Green methanol	Synthesis from green H2 and CO_2	Very low	Very low	19.7	Modified engines	Autonomy, toxicity
Ammonia	Synthesis from green H2 and N_2	Zero	High NOx / 0 SOx	18.6	In development	Toxicity, complex combustion
Hydrogen	Electrolysis from renewables	Zero	Negligible	120 (but low density)	In development (fuel cells)	Storage and safety

Table 2*- summarizes key alternative fuels for maritime shipping*

3.3. Key components and technologies: engines, scrubbers, alternative propulsion systems, digitalization.

The energy and environmental transition of the maritime sector cannot be separated from a profound innovation of the technological components that constitute the heart of the ship system. Among these, main and auxiliary engines, exhaust gas treatment systems (scrubbers), alternative propulsion solutions and digital technologies for the optimized management of operations are of particular importance. The integration of these technologies represents not only an opportunity to reduce the environmental impact of navigation, but also a strategic step to ensure competitiveness in a market increasingly oriented towards ESG criteria and stringent regulations.

Marine engines, historically based on two-stroke diesel cycles (main engines) or four-stroke (auxiliary engines), are now at the centre of a structural transformation. The most modern versions are designed according to dual-fuel configurations, capable of operating with a combination of traditional and alternative fuels (such as LNG, methanol or biofuel), thus allowing greater flexibility and resilience to fluctuations in the energy market and environmental policies. Major ship engine manufacturers, such as MAN Energy Solutions and Wärtsilä, are investing heavily in engines compatible with low- and zero-emission fuels, and in the development of modular engines that can be upgraded as the available energy mix evolves. From a technical point of view, the design of these engines includes the optimization of compression ratios, electronic combustion management and integration with thermal energy recovery systems, to increase efficiency and reduce specific emissions.

Alongside engines, emission abatement systems, known as scrubbers, play a key role. These are devices installed in the exhaust system of ships that allow the removal of sulphur oxides (SO_x) from exhaust gases, making it possible to use fuels with a high sulphur content (such as HFO) while respecting the limits imposed by MARPOL regulations. There are mainly two types of scrubbers: open-loop, which uses seawater and discharges the treated residues directly into the sea, and closed-loop, which treats and recycles washing water in a closed loop. While scrubbers have enabled relatively rapid compliance with the 2020 Sulphur Cap regulation, their secondary environmental impact (especially in open-loop mode) and associated operating costs are raising growing questions about their long-term sustainability.

Alternative propulsion is another crucial area of innovation. In addition to diesel-electric hybrid systems, fuel cell-based solutions, high-capacity batteries, full-electric engines, and wind-assisted energy approaches, such as automated rigid sails (e.g., Flettner rotors, wing sails) and tow kites, are emerging. Fuel cells allow the direct production of electricity from fuels such as hydrogen, methanol, or ammonia without combustion and with zero or near-zero emissions. The main challenges remain related to energy density, cell life, hydrogen safety and the availability of compatible fuels. Battery solutions, on the other hand, are currently limited to short-sea shipping and electric ferries due to the low energy density compared to liquid fuels.

Finally, the digitalisation of ship operations is a cross-cutting enabler for the efficiency and sustainability of maritime transport. The integration of real-time monitoring systems, route optimization platforms, digital twins and machine learning applied to predictive maintenance makes it possible to reduce energy consumption, minimize unscheduled stops and manage on-board resources in a more rational way. In addition, digital technologies are essential for environmental monitoring and reporting (e.g. CII, EEXI, EU ETS), as they allow performance data to be collected and transmitted accurately and in compliance with regulations. Finally, the combined use of artificial

intelligence and predictive models allows advanced simulations of the ship's behavior in different operating conditions, facilitating the choice of the most sustainable and cost-effective solutions.
The modernization of the technical components of ships – from engines to abatement systems, from alternative propulsion to digitalization – is today an indispensable condition for the transition of the shipping sector towards a future with low or zero emissions. The speed of deployment and interoperability between these technologies will determine the pace and scale of maritime decarbonisation in the medium to long term.

3.3.1. Marine engines

Marine engines represent the most critical technological component within the ship system, as they largely determine the energy and emission profile of the entire unit.
Traditionally, naval propulsion has relied on internal combustion engines, predominantly two-stroke diesel for the main propulsion and four-stroke diesel for the auxiliary units intended for on-board electrical generation[274].
Two-stroke engines are characterized by a thermodynamic cycle that completes the phases of intake, compression, combustion and expulsion of gases in just two movements of the piston. Operation is based on the intake of compressed air into the cylinder through side valves or ports in the cylinder itself, compression and subsequent direct injection of the fuel (usually HFO or MDO), high-pressure ignition and combustion, expansion and finally exhaust of the flue gases through the exhaust valve located at the head of the cylinder[275]. Two-stroke engines, with operating speeds between 60 and 120 rpm, are optimized for efficiency in continuous navigation and can achieve thermal efficiencies of more than 50%, while four-stroke engines, which are more compact and operate at higher speeds (up to 1500 rpm),[276] are less efficient but more versatile for on-board applications.
In terms of specific consumption, a modern two-stroke marine diesel engine consumes an average of between 160 and 190 g/kWh of fuel. This translates, on a large 10,000 TEU container ship, into a daily consumption that can exceed 200 tons of fuel oil when sailing at cruising speed. In terms of emissions, the use of traditional fuels involves the release into the atmosphere of about 3,114 kg of CO_2 for every ton of fuel oil consumed (according to IPCC standard factors). For a large ship, this equates to 6,000–7,000 tonnes of CO_2 per week, not counting other pollutants such as sulphur oxides

[274] International Renewable Energy Agency. (2021). *A pathway to decarbonise the shipping sector by 2050*. IRENA
[275] RINA. (2024, January). *La rotta verso il Net Zero. Insieme per decarbonizzare il settore marittimo* (Rev. 01). Eni, Assarmatori, Confitarma, Wärtsilä, Man Energy Solutions, WinGD, Federchimica/Assogasliquidi, Unem, Assocostieri. Supervisione a cura di RINA.
[276] Beduschi, S., Allieri, E., Soria, D., Rossi, F., Migliorini, S., Lentini, M., et al. (2024). *The route to net zero. Together to decarbonise the maritime sector* (Rev. 01 – January 2024). RINA, Assarmatori, Confitarma, Eni.

(SO_x) and nitrogen oxides (NO_x), which are around 50–100kg per tonne of fuel respectively, in the absence of abatement systems[277].

Four-stroke engines, on the other hand, are a fundamental component for on-board electrical generation and for the propulsion of small and medium-sized ships, such as ferries, supply vessels or passenger units. Their operation is based on a thermodynamic cycle in four phases – intake, compression, combustion and expulsion – which take place in four piston strokes and two revolutions of the crankshaft. During the intake phase, an inlet valve opens to let air (or the air-fuel mixture in dual-fuel engines) enter the cylinder[278]; This is followed by the compression phase, in which the piston rises, compressing the air charge. Fuel injection takes place at high pressure just before the top dead center, causing the fuel to self-ignite in the case of diesel engines. In the next phase, combustion generates the expansion of gases that push the piston downwards, transforming thermal energy into mechanical work[279]. Finally, the piston rises, expelling the flue gases through the exhaust valve.

These motors normally operate at speeds between 400 and 1,200 rpm, making them suitable for applications where greater operational flexibility and fast response to varying loads are required. Compared to two-stroke engines, four-strokes have a more compact design, higher power density per unit volume and greater versatility in the use of alternative fuels, but at the expense of lower thermal efficiency, which is generally around 40–46%[280].

From the point of view of specific fuel consumption (SFOC), four-stroke engines show values between 185 and 210 grams per kilowatt hour (g/kWh), compared to 160–180 g/kWh for two-strokes. This means that, for the same amount of energy produced, they consume about 10–15% more than two-stroke engines. However, the increased flexibility in load management and ease of ignition make them ideal for powering ancillary systems, where marginal efficiency is offset by the need to operate in a discontinuous or modular manner.

In terms of emissions, four-stroke engines powered by conventional fuels (MDO, MGO) generate a significant amount of CO_2, with an average emission factor of around 3.2 tonnes of CO_2 per tonne of fuel. In addition, they produce NO_x in amounts ranging from 10 to 20 g/kWh, depending on the load and injection system, and particulate matter (PM) between 0.2 and 0.5 g/kWh in the absence of

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[277] Beduschi, S., Allieri, E., Soria, D., Rossi, F., Migliorini, S., Lentini, M., et al. (2024). *The route to net zero. Together to decarbonise the maritime sector* (Rev. 01 – January 2024). RINA, Assarmatori, Confitarma, Eni.

[278] Dere, C. (2023). *Hydrogen fueled engine technology, adaptation, and application for marine engines*. *Energies, 16*(641), 1–26.

[279] Natali, M., & Rego, R. (2023). *Ship engine, equipment and fuel options for decarbonization*. In RINA – Royal Institution of Naval Architects, *Maritime Decarbonization Conference Proceedings* (pp. 1–16). London: RINA.

[280] Natali, M., & Rego, R. (2023). *Ship engine, equipment and fuel options for decarbonization*. In RINA – Royal Institution of Naval Architects, *Maritime Decarbonization Conference Proceedings* (pp. 1–16). London: RINA.

filtration systems[281]. The adoption of optimized combustion technologies, such as common rail systems, multiple post-injection and variable valve timing, improves combustion quality and reduces unwanted emissions. In addition, after-treatment systems such as SCR (Selective Catalytic Reduction) catalysts for NO_x abatement or DPF (Diesel Particulate Filter) for the containment of fine particulate matter can be installed.

With the tightening of international emission regulations, such as MARPOL Annex VI and the EEDI and EEXI indices, technological evolution in the marine propulsion sector has shifted towards more advanced and efficient solutions, including dual-fuel engines. These systems, designed to work with both liquid fuels (such as MGO) and gaseous fuels (such as LNG), make use of two distinct power circuits that allow flexible and modular energy management on board. In gas mode, operation takes place according to a principle like the Otto cycle: the methane is premixed with air before entering the cylinder and triggered by a small amount of pilot diesel, ensuring cleaner and thermally controlled combustion. This configuration makes it possible to almost completely reduce sulphur oxide (SO_x) emissions, reduce nitrogen oxides (NO_x) by up to 85% and almost eliminate particulate matter. In addition, CO_2 emissions are 20–25% lower than conventional diesel engines, at least in the *tank-to-wake* phase. However, this technology is not without limitations: the thermal efficiency is slightly lower than that of optimized diesels, and the possibility of methane slip, i.e. the release of methane that is not completely burned, is a significant criticality. This phenomenon partly compromises the environmental benefits, since methane has a climate-changing potential (GWP) about 84 times higher than CO_2 over a time horizon of twenty years. Despite this, dual-fuel engines today represent one of the most consolidated technical solutions for the energy transition in the naval sector, thanks to their operational versatility and compatibility with rapidly developing bunkering infrastructures.

Among the most innovative solutions for the decarbonization of maritime propulsion are internal combustion engines compatible with alternative fuels, such as methanol, ammonia and hydrogen[282]. These systems, based on the same mechanical architecture as conventional diesel engines, nevertheless require significant changes to the fuel system, combustion chamber geometry and electronic management of the engine cycle. Methanol, for example, is a liquid fuel that can be injected directly into the cylinder during compression or premixed with air in spark-ignition engines. In both cases, its relatively low ignition temperature (around 470 °C) and miscibility with water promote stable and cleaner combustion than conventional fuels. However, due to its low calorific value (about 19.7 MJ/kg), consumption is higher: it is estimated that to obtain the same useful energy provided by

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[281] Sevim, C., & Zincir, B. (2023). *Lifecycle emissions of fossil fuels and biofuels for maritime transportation: A requirement analysis*. In Proceedings of the International Maritime Science Conference (IMSC 2023), Dubrovnik, Croatia
[282] Global Maritime Forum. (2022). *A zero-emission blueprint for shipping*. Getting to Zero Coalition.

diesel, an engine must consume up to 2.2 times more methanol per MWh produced. On the other hand, SO_x and PM emissions are drastically reduced, and CO_2 can be reduced to zero if the fuel is of synthetic origin (e-methanol).[283]

Ammonia-powered engines, on the other hand, pose an even more complex challenge. Ammonia can be used both as a direct fuel in spark-ignition engines and in compression engines with direct injection or double injection with pilot fuel. However, its low responsiveness, coupled with a calorific value of only 18.6 MJ/kg, requires high injection pressures, modified combustion chambers, and advanced ignition strategies. The volumetric consumption is high, and the nominal power of the engine is lower for the same displacement. Ammonia, although it does not contain carbon and therefore does not generate CO_2 during combustion, produces high NO_x emissions, due to high temperatures and the presence of nitrogen in the molecule, which require the use of advanced after-treatment systems (e.g. SCR). In addition, the toxicity and corrosiveness of ammonia impose strict safety measures on board. In the case of hydrogen, ICE engines can operate with both direct injection and positive ignition. Hydrogen has the highest calorific value per mass (about 120 MJ/kg), but a very low energy density per volume, which makes its storage complex (it requires pressures up to 700 bar or temperatures of –253 °C in liquid form). The operation of the hydrogen engine is technically like that of natural gas engines, but the hydrogen flame is extremely reactive and difficult to control, with a risk of detonation. From an environmental point of view, hydrogen does not generate CO_2, nor SO_x, nor PM, but it can produce NO_x in high-temperature conditions, requiring lean or EGR-diluted cooling and combustion strategies. Volumetric consumption is high, and thermal efficiencies are similar to those of gas engines, with values between 40 and 45%.[284]

At the same time, technological evolution is also affecting the mechanics and control of the motors themselves, as demonstrated by camless motors. In these systems, the absence of the traditional camshaft is compensated using electro-hydraulic or electromagnetic actuators that manage the opening and closing of the intake and exhaust valves in a completely independent and variable way. The same applies to fuel injection, regulated by electronic control units that optimize parameters in real time based on operating conditions. This allows dynamic combustion management, which can be calibrated to reduce consumption in partial loads, contain NO_x emissions thanks to advanced or delayed valve timing, and improve acoustic comfort and vibrations. From a fuel consumption perspective, camless engines offer an efficiency gain of up to 3–5% compared to equivalent

[283] European Environment Agency. (2019). *The European environment — state and outlook 2020: Knowledge for transition to a sustainable Europe*. Publications Office of the European Union

[284] Global Maritime Forum. (2022). *A zero-emission blueprint for shipping*. Getting to Zero Coalition.

mechanical engines[285], while emissions can be reduced without compromising power, especially in lean-burn or Miller configurations. The absence of complex mechanical components such as the camshaft and rocker arms also reduces the need for maintenance and extends its service life.

Finally, one of the most significant developments in the design of marine propulsion systems is the integration of internal combustion engines with *Waste Heat Recovery (WHR)* systems[286]. These systems use the heat contained in high-temperature exhaust gases, typically above 300–400 °C, to generate steam in a Heat Recovery Steam Generator (HRSG)[287]. The steam produced is then used to power a steam turbine connected to an electric alternator or to support other thermal processes on board (e.g. tank heating, air conditioning, desalination). In more advanced configurations, the recovered thermal energy can also be used in cogeneration systems (CHP) or in organic fluid Rankine cycles (ORC), which are particularly effective on ships with constant thermal and electrical loads.

The main advantage of WHR systems lies in their direct contribution to the energy balance of the ship: by producing electricity or useful work from a source that would otherwise be dissipated, they allow a reduction in the load on auxiliary engines or diesel generators. This translates into a decrease in fuel consumption of up to 10% daily, depending on the operating profile of the ship and the sizing of the system. For example, a large 14,000 TEU container ship, consuming over 150–200 tons of fuel per day, can save an average of 15–20 tons per day thanks to the integration of a well-designed WHR system[288].

From an emissions point of view, the benefit is proportional to the fuel saved: each ton of fuel oil avoided leads to a reduction of about 3.1 tons of CO_2, as well as a direct decrease in NO_x, SO_x and particulate emissions[289]. WHRs do not directly produce emissions but help reduce the total emissions of the ship by lowering the energy needs met through combustion. The efficiency of the systems can vary from 5 to 15% of the energy content of the exhaust gases, and the adoption of intelligent adjustments optimizes their efficiency even under partial or variable load conditions[290].

This evolution represents a key step towards a systemic approach to maritime propulsion, in which the engine is no longer an isolated entity, but an integral part of an integrated and optimized energy

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[285] Skoko, I., Stanivuk, T., Franic, B., & Bozic, D. (2024). Comparative Analysis of CO_2 Emissions, Fuel Consumption, and Fuel Costs of Diesel and Hybrid Dredger Ship Engines. *Journal of Marine Science and Engineering, 12*(6), 999

[286] Torreglosa, J. P., Vera, D., López-García, D. A., Pérez Vallés, A., Hernández-Torres, J. A., & Clavijo-Camacho, J. *MVDC electric propulsion systems for integrating waste heat recovery systems in marine transport* (Unpublished manuscript). Department of Electrical Engineering, University of Huelva.

[287] Singh, D. V., & Pedersen, E. (2016). A review of waste heat recovery technologies for maritime applications. *Energy Conversion and Management, 111*, 315–328.

[288] DNV. (2023). *Waste heat recovery systems in the maritime sector: Current status and future potential*.

[289] Skoko, I., Stanivuk, T., Franic, B., & Bozic, D. (2024). Comparative Analysis of CO_2 Emissions, Fuel Consumption, and Fuel Costs of Diesel and Hybrid Dredger Ship Engines. *Journal of Marine Science and Engineering, 12*(6), 999.

[290] European Environment Agency. (2019). *The European environment — state and outlook 2020: Knowledge for transition to a sustainable Europe*. Publications Office of the European Union

ecosystem. The engine, auxiliary and control systems now form a synergistic network, which aims to maximize efficiency and minimize environmental impact. The consumption and final emissions of a ship no longer depend solely on the type of fuel or engine technology adopted, but also on the degree of integration with recovery systems, predictive digitalization and intelligent energy management solutions. The future trend will therefore be to combine high performance, operational versatility and environmental sustainability, through hybrid technologies, multi-fuel engines, advanced heat recovery systems and full compatibility with low- or zero-carbon fuels.

3.3.2. Scrubber

Another key technology for mitigating environmental impact in the marine sector is exhaust gas abatement systems, commonly known as scrubbers. These devices are designed to mainly remove sulphur oxides (SO_x) from the fumes emitted by internal combustion engines, making it possible to use high-sulphur fuels (HFOs), while complying with the limits imposed by MARPOL Annex VI, such as the Sulphur Cap 2020, which sets 0.5% as the global maximum sulphur content in marine fuels[291]. Scrubbers are installed downstream of the exhaust system of the main engine, auxiliary generators or boilers, and operate through a process of flushing the gases with water (sea or freshwater), which neutralizes and absorbs the acidic compounds present in the fumes.
From a technical point of view, there are mainly three types of scrubbers: open-loop, closed-loop and hybrid[292]. Each has specific operating characteristics that affect environmental efficiency, engineering requirements, ancillary consumption and overall cost of ownership. The choice between different solutions depends on operational factors, trade routes, local regulations and the owner's economic strategy.

- Open-loop, it is the simplest and most widespread configuration, especially between 2018 and 2020, due to the rapid need to adapt to the IMO Global Sulphur Cap. In this case, seawater is taken, pumped into the washing tower, and used to neutralize gases containing SO_2 and SO_3 by chemical reactions that generate sulphites and sulphates, exploiting the natural alkalinity of seawater. After the process, the water is filtered and discharged back into the sea.
  From an energy point of view, the consumption of open-loop systems is limited to the electric motors of the circulation pumps, with absorptions ranging from 50 to 200 kW, depending on

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[291] Allwright, G. (2023). *Green shipping corridors: Opening the door to zero-emission fuels and technologies*. Bunkerspot, 20(2), 34–36.
[292] Vidović, T., Šimunović, J., Radica, G., & Penga, Ž. (2023). Systematic overview of newly available technologies in the green maritime sector. *Energies, 16*(2), 641.

the power of the main motor and the size of the system. This results in an increase in fuel consumption of the order of 1–2% per day[293]. SO_x abatement efficiency can reach 98–99%, allowing the use of high sulphur fuels (HFOs) even in areas where the limit is set at 0.5%.[294] However, the direct release of wash water containing heavy metals, hydrocarbons and dissolved particulate matter into the sea has led several countries and ports to ban or restrict the use of open-loops, particularly in coastal and port waters[295].

- Closed-loop, they are designed to operate in a closed loop, using a mixture of fresh water and alkaline reagent – usually caustic soda (NaOH) – for the neutralization of acid gases. The water is recirculated through the system, cooled and treated internally by separators and filters, minimizing or eliminating release into the sea. Only a small amount of contaminated water (blowdown) is periodically discharged and must be disposed of in accordance with regulations.

  This configuration involves increased plant complexity, with heat exchangers, additional pumps, reagent dosers, filtration systems and chemical neutralization units. Electricity consumption is higher than open-loop, reaching as high as 250–300 kW on large ships, with an impact of 2–3% on daily consumption[296]. However, the environmental impact is much lower, and the system can be used in all waters, including port areas and areas subject to environmental restrictions. Operating costs also include the chemical reagent, with typical consumption of 2–4 litres of NaOH per tonne of fuel burned[297].
- Hybrid, represent a flexible solution, capable of operating in both open-loop and closed-loop mode, depending on environmental, regulatory and operational conditions. The transition between the two modes can be managed automatically through the control system. In the open sea, where there are no restrictions, you can operate in an open-loop to minimize costs; in port or in ECA areas, we switch to closed-loop mode to comply with regulatory constraints.

  From a technical point of view, hybrid systems require more space on board, switching systems between the two regimes, dedicated tanks for reagents and washing water, and greater integration into on-board systems. Energy consumption is comparable to that of closed-loop systems (up to 300 kW), but operational adaptability is a competitive advantage, especially

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[293] ABS. (2019). *Scrubber Systems: Guidance on Best Practices for Installation and Operation*. American Bureau of Shipping

[294] BOTTOM. (2020). *2020 Global Sulphur Limit*. International Maritime Organization

[295] The ICCT. (2020). *Air pollution from ships: Impact of scrubbers on marine water quality*. International Council on Clean Transportation

[296] DNV. (2021). *Exhaust Gas Cleaning Systems: Trends and Challenges*. Det Norske Veritas

[297] Vidović, T., Šimunović, J., Radica, G., & Penga, Ž. (2023). Systematic overview of newly available technologies in the green maritime sector. *Energies.*

for ships operating on global routes and complying with different regulations. The initial investment is higher, but it can be amortized through fuel savings and increased environmental compliance[298].

Scrubber operation involves the exhaust gases being passed through a scrubbing tower where they encounter the scrubber fluid[299]. Acidic compounds (SO_2, SO_3) dissolve in water and chemically react to form sulphites and sulphates, which are then separated and treated. The SO_x removal efficiency can reach 98–99%, making the outgoing gases comply with even the most stringent limits (0.1% S) of the ECAs – Emission Control Areas. Scrubbers do not remove CO_2, but they can marginally contribute to the reduction of particulate matter and, in some cases, some polycyclic aromatic hydrocarbons (PAHs) present in the flue gases.
However, environmental and regulatory issues have emerged, particularly regarding open-loop systems. Several countries and port authorities – including China, Singapore, Germany and some coastal regions of the United States – have banned or restricted their use because of wastewater, potentially contaminated with heavy metals, PAHs and sulphates, on marine ecosystems[300]. In addition, the management of wash residues and sludge requires the development of strict protocols for onshore disposal. In the future, the effectiveness of scrubbers will not only be assessed in terms of SO_x abatement but also considering the environmental life cycle of the system, the impact on marine biodiversity, and the cost-effectiveness in the context of a transition to zero-emission fuels[301].

3.3.3. Alternative propulsion systems

As environmental concerns and regulatory pressures increase, the shipping industry is actively seeking alternative propulsion systems that promise to mitigate the environmental impact of shipping and redefine the way ships traverse oceans. These innovative propulsion methods are diverse, including both the fuels that power them and the technologies that convert energy into motion[302].
One of the most significant changes in marine propulsion is the shift to electrification. Electric propulsion systems, which can include battery and hybrid engines, offer the promise of emission-free operation, especially when paired with renewable energy sources. Advances in battery technology

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298 Wärtsilä. (2020). *Exhaust Gas Cleaning Systems – Product Guide*
299 Allwright, G. (2023). *Green shipping corridors: Opening the door to zero-emission fuels and technologies*.
300 EMSA. (2020). *Evaluation of the Impact of Scrubber Wash Water Discharges on the Marine Environment*. European Maritime Safety Agency
301 DNV. (2021). *Exhaust Gas Cleaning Systems: Trends and Challenges*. Det Norske Veritas
302 Zanobetti, F., Pio, G., Jafarzadeh, S., Ortiz, M. M., & Cozzani, V. (2023). *Decarbonization of maritime transport: Sustainability assessment of alternative power systems*. Energies.

allow for greater range and higher power capabilities, allowing vessels, especially those on short routes, to operate completely without combustion engines[303].

Hybrid propulsion systems are another area of development, combining internal combustion engines with electric motors. These systems can switch between or use energy sources at the same time, such as diesel and batteries, to optimize fuel consumption and reduce emissions. The flexibility of hybrid systems is particularly attractive for vessels that have different operating profiles, such as those that need to alternate between high-speed and low-speed manoeuvres[304].

Wind-assisted propulsion[305] is experiencing a renaissance with modern technology breathing new life into centuries-old sailing concepts. Equipping ships with sails, kites or rotors can harness the natural power of the wind, significantly reducing dependence on fossil fuels. These systems are increasingly seen not as a primary source of thrust, but as a complementary force capable of reducing fuel consumption and emissions[306].

Solar energy is also making its way into marine propulsion, with photovoltaic cells used to generate electricity to power on-board systems and, in some cases, provide auxiliary propulsion. While solar power alone may not be enough to propel large ocean-going vessels, it can be particularly effective for smaller vessels or in combination with other energy sources[307].

Nuclear propulsion, which has been used in military vessels, is occasionally considered for commercial shipping due to its ability to provide constant power without emissions. However, safety issues, regulatory constraints and public perception have limited its application in the commercial sector[308].

Innovations in mechanical propulsion systems, such as advanced propeller design and hull shapes, are also contributing to the overall efficiency of ships. These technologies aim to reduce drag, improve hydrodynamics and maximize thrust, thus reducing the energy required for propulsion.

In all these advances, the integration of smart technologies and automation plays a crucial role. Modern ships equipped with advanced navigation and control systems can optimize routes, speed,

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[303] Inal, Ö. B., Charpentier, J.-F., & Deniz, C. (2023). *Electrification and hybridization of ferries: State of the art and case study*. Energies.

[304] Inal, Ö. B., Charpentier, J.-F., & Deniz, C. (2023). *Electrification and hybridization of ferries: State of the art and case study*. Energies.

[305] International Windship Association (IWSA), Comoros, France & Solomon Islands. (2024). *White paper on wind propulsion submitted to MEPC81*. MEPC 81/INF.39, International Maritime Organization.

[306] Hoffmeister, H., Hollenbach, U., Tranell, J., Aalbu, K., Skåre, O. G., Endresen, Ø., Stefanatos, J., Kvålsvold, J., Hustad, H., Wienke, J., Leisner, M., & Schäfer, J. (2025). *Wind-assisted propulsion systems (WAPS): How WAPS can help to comply with GHG regulations*. DNV – Det Norske Veritas.

[307] Zanobetti, F., Pio, G., Jafarzadeh, S., Muñoz Ortiz, M., & Cozzani, V. (2023). *Decarbonization of maritime transport: Sustainability assessment of alternative power systems*. *Energies*

[308] Zanobetti, F., Pio, G., Jafarzadeh, S., Muñoz Ortiz, M., & Cozzani, V. (2023). *Decarbonization of maritime transport: Sustainability assessment of alternative power systems*. *Energies*

and energy consumption, further enhancing the efficiency gains provided by alternative propulsion methods.

The transition to alternative propulsion systems is not simply a matter of replacing one fuel or technology with another; It is a complex process that involves rethinking ship design, operations, and maritime infrastructure in general. It requires a coordinated effort between shipbuilders, operators, fuel suppliers and regulators to create an ecosystem that supports these new technologies. The goal is to realize a maritime industry that can sustain its vital role in global trade, operating harmoniously within the Earth's ecological boundaries.

3.3.4. Renewable energy and electrification

The maritime industry, which is a significant contributor to global CO2 emissions, is on the verge of a revolutionary shift towards sustainability through renewable energy and electrification. This transition is not just an environmental imperative, but a strategic adaptation to evolving global standards and consumer expectations. The integration of renewable energy sources such as wind, solar and biofuels into maritime operations is a key step towards reducing the carbon footprint of shipping activities. Wind propulsion technologies, for example, have seen a renaissance through modern engineering marvels such as rotor sails and kites, harnessing natural wind energy to significantly reduce fuel consumption. Solar power, although less powerful due to space limitations on ships, provides auxiliary power for onboard systems, further reducing the use of diesel generators. Biofuels, derived from sustainable sources, are a viable transition fuel, compatible with existing engines but offering a substantial reduction in carbon emissions. The scalability of these renewables depends on technological advancements and infrastructure support, underscoring the need for industry-wide collaboration and innovation[309].

Electrification emerges as a cornerstone of the industry's decarbonization efforts, extending from ships to port operations. Electric propulsion systems, powered by batteries or fuel cells, promise a zero-emission solution for short-sea and inland shipping. These systems are particularly effective in reducing air pollution in densely populated port cities and sensitive ecological areas.

Shore-side electricity, or cold ironing, allows docked ships to draw power from the grid, eliminating the need to run diesel engines for electricity, thereby reducing port emissions. The expansion of this technology depends on the availability of renewable energy in the grid and port infrastructure,

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[309] Zanobetti, F., Pio, G., Jafarzadeh, S., Muñoz Ortiz, M., & Cozzani, V. (2023). *Decarbonization of maritime transport: Sustainability assessment of alternative power systems*. *Energies*

highlighting the interconnection of maritime and land-based energy systems. Despite the obvious benefits, the transition to renewable energy and electrification faces significant challenges. High upfront costs, the need for global regulatory frameworks, and technological barriers in energy storage and efficiency are among the main obstacles. However, these challenges also present opportunities for innovation, investment, and leadership in green shipping practices.

Incentives and regulations play a crucial role in accelerating the adoption of green technologies. The International Maritime Organization (IMO) sets ambitious targets for reducing greenhouse gas emissions, pushing the industry towards cleaner alternatives. National and regional policies, including grants, tax incentives and research grants, further encourage the shift to renewable energy and electrification[310]. The maritime industry's journey towards renewable energy and electrification is challenging and essential. It requires a concerted effort by shipbuilders, operators, regulators and technology providers to overcome existing barriers. With the right mix of innovation, policy advocacy, and global cooperation, the industry can achieve significant emissions reductions, paving the way for a sustainable and prosperous future.

3.3.5. Innovative materials and coatings

The shipping industry is increasingly turning to innovative materials and coatings as a means of improving the performance, durability and environmental sustainability of ships. These advances are critical to addressing the myriad challenges ships face, including corrosion, biofouling, and the need for energy efficiency. By integrating state-of-the-art materials and surface treatments, shipping companies can significantly reduce maintenance costs, improve fuel efficiency, and minimize their environmental impact.

One of the most critical areas of innovation is the development of antifouling and anti-corrosion coatings[311]. Traditional antifouling paints, which release toxic substances to prevent the growth of organisms, are being phased out in favor of more environmentally friendly alternatives. The new coatings use advanced materials such as silicone or fluoropolymer composites that create a slippery surface, making it difficult for organisms to adhere and easier for any biofouling to be washed away by the vessel's movement. These coatings not only reduce the resistance caused by biofouling, resulting in lower fuel consumption and emissions, but also decrease the frequency and need for dry dock cleaning, thereby reducing operating costs.

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[310] International Maritime Organization. (2023). *IMO strategy on reduction of GHG emissions from ships*.
[311] HIPER'24 Organizing Committee. (2024, June 10–12). *Proceedings of the 16th Symposium on High-Performance Marine Vehicles (HIPER'24)*, Drübeck, Germany.

Corrosion resistance is another critical area where innovative materials are having a significant impact. High-performance alloys, composite materials and advanced protective coatings are being developed to extend the life of ships and their components. These materials are designed to withstand harsh marine environments, reducing the need for repairs and replacements and ensuring structural integrity for longer periods.

The shipbuilding industry is also exploring the use of lightweight materials, such as aluminium alloys and fiber-reinforced polymers, in shipbuilding. These materials can significantly reduce the overall weight of a boat, improve fuel efficiency and reduce greenhouse gas emissions. However, their use must be carefully balanced with safety considerations, particularly regarding fire resistance and structural strength[312].

In addition to structural materials, there is a growing interest in incorporating smart coatings and materials that can self-heal, change colour in response to damage, or release anti-corrosive agents after detecting a breach. These smart materials can greatly improve maintenance efficiency and safety by providing early warning of potential issues before they become critical.

The integration of photovoltaic (solar) panels in the design of ship surfaces presents another frontier in the use of innovative materials. By harnessing solar energy, ships can generate a portion of their energy needs, reducing their reliance on fossil fuels and contributing to the industry's sustainability goals. The drive towards innovation of materials and coatings in maritime transport is not only a response to environmental and operational challenges, but also a strategic investment in the future competitiveness of the sector. As emissions and environmental protection regulations tighten and energy and maintenance costs rise, the adoption of these advanced materials and coatings will play a crucial role in ensuring the sustainability and efficiency of global shipping operations. Collaboration between shipbuilders, materials scientists, and maritime regulators is essential to accelerate the development and adoption of these technologies, paving the way for a more sustainable and efficient maritime industry.

3.3.6. Innovations in ship design and fuel efficiency

Innovations in ship design and fuel efficiency are critical to the marine industry's response to environmental challenges and sustainability goals. The European Commission has been at the

[312] HIPER'24 Organizing Committee. (2024, June 10–12). *Proceedings of the 16th Symposium on High-Performance Marine Vehicles (HIPER'24)*, Drübeck, Germany.

forefront of supporting research and innovation in this area, recognising that smarter, lighter and more fuel-efficient ships are key to a sustainable future[313].

One of the main initiatives supported by the European Commission's research and innovation projects is the development of lighter boats using advanced materials. The use of high-strength steel and composites can significantly reduce the weight of ships, resulting in lower fuel consumption and emissions. Lighter vessels require less energy to move, which directly translates into fuel savings and reduced operating costs. Additionally, advanced materials can offer increased durability and reduced maintenance requirements, improving the overall efficiency and durability of vessels.

Ship design also plays a vital role in improving fuel efficiency. Innovations such as optimized hull shapes, which reduce drag, and advanced coatings that prevent biofouling can further reduce fuel consumption. Increased hydrodynamic efficiency means ships can travel faster and with less drag, resulting in lower fuel consumption and emissions per trip[314].

Fuel efficiency is also improved through the integration of propulsion technologies such as hybrid engines, which combine traditional internal combustion engines with battery power to reduce fuel consumption during specific operating conditions, such as manoeuvring in ports or operating at low speeds[315]. Other technological advancements include air lubrication systems, which reduce drag between the hull and the water by creating a carpet of air bubbles under the boat.

Energy recovery systems are another area of innovation. Technologies that capture and reuse heat from engine exhaust, which would otherwise be lost, contribute to the overall energy efficiency of ships. These systems can be used for heating or even to generate additional energy.

Digitalization and smart technologies also help to improve fuel efficiency. Advanced navigation systems and route optimization software can predict the most fuel-efficient routes, considering weather conditions, currents and other environmental factors. The use of sensors and data analytics allows for real-time monitoring and management of fuel consumption, allowing adjustments to be made on the fly to improve efficiency.

In addition, the transition to new energy sources is driving innovation in ship design. The prospect of using alternative fuels such as LNG, hydrogen and ammonia is influencing the development of new types of fuel tanks and distribution systems, as well as propulsion units specifically designed for these fuels. It is important to note that while the focus on lighter materials and advanced design is

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313 https://projects.research-and-innovation.ec.europa.eu/en/projects/success-stories/all/lighter-fuel-efficient-ships-sustainable-future

314 Vidović, T., Šimunović, J., Radica, G., & Penga, Ž. (2023). Systematic overview of newly available technologies in the green maritime sector. *Energies, 16*(2), 641.

315 HIPER'22 Organizing Committee. (2022, August 29–31). *Proceedings of the 14th Symposium on High-Performance Marine Vehicles (HIPER'22),* Cortona, Italy.

promising, it must be aligned with safety regulations and performance standards. Therefore, these innovations are often developed in collaboration with regulatory bodies to ensure that they meet all the necessary criteria for safe operation.
In conclusion, the marine industry's drive towards fuel efficiency and sustainability is supported by a range of innovations in ship design, from the use of new materials and hull designs to the integration of hybrid propulsion systems and advanced digital technologies. These advances are vital not only to reduce the environmental impact of maritime transport, but also to ensure its economic viability in a future where efficiency and sustainability are increasingly valued.

3.3.7 Digitalization and maritime operations

The maritime industry is on the cusp of a digital revolution, with emerging technologies paving the way for unprecedented efficiencies, safety, and environmental sustainability. The digitalization of maritime operations encompasses a broad spectrum of technologies, including artificial intelligence (AI), the Internet of Things (IoT), blockchain, and autonomous systems, each of which plays a critical role in transforming traditional practices[316].
The adoption of AI and IoT technologies is improving predictive maintenance, cargo handling, and fleet management, enabling real-time monitoring and data-driven decision-making[317]. These technologies facilitate route optimization, fuel consumption reduction, and predictive maintenance programs, significantly reducing operating costs and environmental impact.
Blockchain technology further contributes to this transformation by introducing transparency and security in maritime logistics, streamlining documentation processes, and ensuring the integrity of supply chains.
Blockchain technology is emerging as a game-changer in the field of supply chain management, particularly within the intricate networks of maritime logistics[318]. This digital ledger system, featuring decentralized and immutable transaction recording, offers an innovative approach to improving transparency, efficiency, and security throughout the global supply chain.
The nature of blockchain as a distributed ledger means that it is suitable for the complex environment of maritime trade, which involves a multitude of stakeholders such as freight forwarders, freight forwarders, port authorities, and customs officials. The technology's ability to provide a transparent

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[316] Craciun, A., Melillo, I., Papadopoulos, F., & Elg, M. (2024). *Digital tools enabling net-zero cruise vessels*. MSC Cruises & Deltamarin. Paper presented at the 15th Symposium on High-Performance Marine Vehicles (HIPER'23).
[317] Saafi, S., Vikhrova, O., Fodor, G., Hosek, J., & Andreev, S. (2022). *AI-aided integrated terrestrial and non-terrestrial 6G solutions for sustainable maritime networking*. IEEE Network.
[318] Di Vaio, A., Varriale, L., Trujillo, L., & Vassallo, G. (2020). "Blockchain technology in the maritime industry: a bibliometric and content analysis of the last decade of research." *Maritime Policy & Management, 48*(8).

and immutable record of transactions ensures that every participant in the supply chain can track the journey of goods with confidence[319].

Autonomous vessels represent one of the most revolutionary advances in the industry[320]. Although still in the early stages of deployment, these ships promise to revolutionize navigation and operational safety by reducing human error, a leading cause of maritime accidents. The Lloyd's Register article and the "Industry Transition Strategy" highlight the potential of these technologies to improve efficiency and safety, while addressing environmental challenges.

Digitalization also extends to regulatory compliance and environmental monitoring, allowing for more effective enforcement of maritime laws and regulations. Advanced tracking and monitoring systems ensure compliance with international emissions standards, helping the industry in its efforts towards decarbonization. Integrating digital technologies into maritime operations is not without its challenges. Cybersecurity emerges as a critical concern, with the increasing reliance on digital systems increasing the risk of cyberattacks. The documents highlight the importance of robust cybersecurity measures to protect sensitive data and ensure the safe operation of seagoing vessels. In addition, the transition to a digitalised industry requires significant investment in technological development, infrastructure and skills training. The maritime sector must address these challenges, fostering collaboration between stakeholders to drive innovation and adoption of digital technologies.

In conclusion, digitalization is reshaping maritime operations, offering transformative solutions to long-standing challenges in terms of efficiency, safety, and environmental sustainability. The path to a fully digitized maritime sector is complex and requires collaborative efforts, substantial investment, and strategic planning. However, the potential benefits, as outlined in the documents reviewed, are immense and promise a future in which maritime operations will be more efficient, safer and more sustainable than ever before.

3.3.8 Autonomous navigation and navigation technologies

The advent of autonomous navigation and navigation technologies represents a significant leap forward for the maritime industry, heralding a new era of efficiency, safety and environmental sustainability. These innovations encompass a wide range of systems and technologies, including advanced sensors, AI-based decision-making algorithms, satellite communications, and sophisticated

[319] Brandt, T., Hutter, D., Maeder, C., & Müller, R. (2021). *Towards a secure and reliable IT-ecosystem in seaports*. Paper presented at the 29th Conference of the International Association of Maritime Economists (IAME 2021).

[320] Martelli, M., Virdis, A., Gotta, A., Cassarà, P., & Di Summa, M. (2021). An outlook on the future marine traffic management system for autonomous ships.

navigation systems, all designed to operate vessels with minimal human intervention[321]. The integration of autonomous technologies promises to revolutionize traditional maritime operations by improving accuracy in navigation, optimizing route planning, reducing fuel consumption and minimizing human error, which is a major cause of maritime accidents. Additionally, autonomous vessels are considered a key component in the industry's efforts to decarbonize, as they can be managed more efficiently to reduce emissions. The potential benefits of autonomous navigation are enormous, but the path to widespread adoption is fraught with challenges. These include regulatory obstacles, as current international maritime law is unable to operate unmanned vessels; technical challenges related to the reliability and robustness of autonomous systems; and cybersecurity risks associated with increasing digitalization.

Despite these challenges, the industry is making great strides toward overcoming these obstacles, with pilot projects and research initiatives underway to test the feasibility and safety of autonomous operations. The development of international regulations to accommodate autonomous ships is also underway, signalling a collective effort to embrace this transformative technology[322]. As autonomous transportation moves from concept to reality, it will undoubtedly reshape the maritime landscape, providing opportunities for innovation and growth, while addressing some of the most pressing challenges facing the industry today[323].

This overview is inspired by the general themes and technological advances discussed in the context of the maritime industry, reflecting the potential impact and considerations of autonomous navigation and navigation technologies.

3.3.9 Safety technologies

The integration of advanced safety and security technologies into maritime transport is a crucial aspect of modern maritime operations, aimed at protecting marine lives, cargo and ecosystems, while ensuring the smooth flow of global trade. This domain encompasses a wide range of systems, practices, and innovations designed to mitigate risks associated with shipping, piracy, environmental hazards, and operational failures[324].

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[321] Martelli, M., Virdis, A., Gotta, A., Cassarà, P., & Di Summa, M. (2021). An outlook on the future marine traffic management system for autonomous ships.

[322] Brandt, T., Hutter, D., Maeder, C., & Müller, R. (2021). *Towards a secure and reliable IT-ecosystem in seaports*. Paper presented at the 29th Conference of the International Association of Maritime Economists (IAME 2021), Rotterdam, Netherlands

[323] Martelli, M., Virdis, A., Gotta, A., Cassarà, P., & Di Summa, M. (2021). An outlook on the future marine traffic management system for autonomous ships.

[324] Caprolu, M., Di Pietro, R., Raponi, S., Sciancalepore, S., & Tedeschi, P. (2020). *Vessels Cybersecurity: Issues, Challenges, and the Road Ahead*. IEEE Communications Magazine.

One of the key technologies in this area is the Automatic Identification System (AIS)[325], which allows ships to automatically transmit and receive identification and position information. AIS improves situational awareness and collision avoidance between vessels, significantly improving the safety of navigation in congested shipping lanes and in poor visibility conditions.

In addition to AIS, Electronic Chart Display and Information Systems (ECDIS)[326] have become standard on deck, providing an integrated navigation system that combines GPS data, electronic navigation charts and radar imagery. ECDIS systems help to plan optimal routes, avoiding hazards and minimizing the risk of grounding or collision. For security against piracy and unauthorized boarding, ships now employ a variety of measures including long-range acoustic devices (LRADs), which can issue verbal warnings or create deterrent sounds over long distances, and physical barriers such as water cannons and barbed wire. In addition, the International Code on Ship and Port Facility Security (ISPS) establishes a comprehensive framework for the assessment and improvement of security measures on board ships and in port facilities.

Maritime cybersecurity has also become a key concern, as ships increasingly rely on digital technologies for navigation, propulsion, and cargo management. Cybersecurity measures are essential to protect against threats that could compromise browsing systems, operational data, or communication networks. Efforts to strengthen maritime cybersecurity include the implementation of robust encryption, intrusion detection systems, and regular security audits to identify and address vulnerabilities[327]. Environmental safety technologies focus on preventing pollution and protecting marine ecosystems. These include ballast water treatment systems to prevent the introduction of invasive species, advanced wastewater treatment plants, and scrubbing systems to reduce sulfur emissions from ship exhausts[328]. In addition, the development of alternative fuels and propulsion technologies, such as liquefied natural gas (LNG), batteries and hydrogen fuel cells, aims to reduce greenhouse gas emissions and the environmental footprint of the maritime industry.

Emergency response and rescue operations have benefited from advances in satellite communication and tracking technologies. Emergency Position Indication Beacons (EPIRBs) and Personal Locator Beacons (PLBs)[329] can instantly alert rescue coordination centres and provide precise location information in the event of a distress situation at sea. The continuous evolution of safety technologies

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[325] https://shipping.nato.int/nsc/operations/news/2021/ais-automatic-identification-system-overview

[326] https://www.marineinsight.com/marine-navigation/what-is-electronic-chart-display-and-information-system-ecdis/

[327] Longo, G., Russo, E., Armando, A., & Merlo, A. (2022). *Attacking (and defending) the Maritime Radar System*

[328] Eichenhofer, J. O., Heymann, E., Miller, B. P., & Kang, K. W. (2020). *In-Depth Security Assessment of Maritime Container Terminal Software Systems*. Journal of Computer Systems.

[329] International Maritime Organization. (2023). *Emergency Position Indicating Radio Beacons (EPIRBs) and Personal Locator Beacons (PLBs) for maritime safety*.

in maritime transport is a testament to the industry's commitment to reducing risk and improving the safety of its operations. Through international collaboration and adherence to regulations set by bodies such as the International Maritime Organization (IMO), the maritime community is committed to achieving higher standards of safety and security, reflecting the dynamic and challenging nature of global shipping operations.

3.4. Upstream Carbon embedded analysis in ships construction: A Perspective for Sustainable Finance.

Within the framework of environmental sustainability assessments applied to the maritime sector, the integration of the analysis of upstream embedded emissions in shipbuilding materials (upstream embedded carbon) is a methodological advancement needed to fill the gaps inherent in traditional approaches based solely on operational (tank-to-wake) emissions. Such an analytical shift allows the assessment boundary to be extended to the cradle-to-gate segment of the life cycle, including environmental externalities arising from the production, processing, and procurement of structural and functional materials. This upstream dimension is of increasing relevance to financial institutions, which need early and granular indicators to identify transition risks along the production chain. In particular, the adoption of embedded carbon metrics makes it possible to anticipate the adequacy of a project with respect to the Technical Screening Criteria defined by the EU Taxonomy, the disclosure obligations introduced by the Corporate Sustainability Reporting Directive (CSRD), and the requirements of the latest generation of ESG frameworks, thus enhancing banks' ability to integrate environmental risk into credit assessment and the structuring of climate-aligned financial instruments.

3.4.1. Selection of ship types and relevant materials

Starting from the classification of types outlined in Section 1, five macro-categories of ship units representative of the contemporary maritime industry were selected: Oil Tanker, Container Ship, Bulk Carrier, LNG Carrier, and Ro-Ro/Pax Ferry. For each type, an estimate of the average material composition under construction was reconstructed using consolidated data from technical reference sources such as IRENA (2021)[330], Global Maritime Forum (2022)[331], and RINA (2024)[332]. The analysis considered the percentage incidence of materials on the total weight of the ship, cross-

[330] International Renewable Energy Agency. (2021). *A pathway to decarbonise the shipping sector by 2050*. IRENA.
[331] Global Maritime Forum. (2022). *2022 Annual Progress Report on Green Shipping Corridors*.
[332] Eni, Fincantieri, & RINA. (2025). *Sustainable maritime transport outlook*.

referenced with the respective emission factors (EF), expressed in $kgCO_2e$ per kg of material[333], to calculate the embedded environmental impact (embedded carbon) associated with construction.
Specifically, the five materials and components with the highest environmental significance in terms of embedded emissions were identified for each type of ship. The selection was based on two key variables: mass quantity and emission intensity of the material. The recurring critical materials turn out to be[334]: steel, aluminium, electronics/wiring, resins/paints and plastics/polymer compounds.
The following tables summarise the results of the analysis:
The first table shows, for each ship type, the selected critical materials and their relevance in terms of carbon embedded. The qualitative classification ("Very relevant", "Relevant", etc.) reflects the potential impact resulting from the intersection of material incidence and carbon intensity. For example, electronics is "very relevant" in LNG Carriers and Ro-Ro/Pax Ferries, where automation and digital systems play a structural role.
The second table, which is of a quantitative nature, presents for each vessel:

- the weighted percentages of materials in the structure.
- their emission factors (EF).
- the embedded emissions calculation (Embedded CO_2e), obtained by multiplying each percentage with the material's EF.

Ship Type	**Relevant Material**	**Relevance Embedded**
Oil Tanker	Steel	Very relevant
	Electronics	Relevant
	Aluminium	Relevant
	Resins/plastics	Moderately relevant
	Other materials	Moderate
Container Ship	Steel	Very relevant
	Electronics	Very relevant
	Aluminium	Relevant
	Plastics/Coatings	Relevant
	Cables/copper	Moderate
Bulk Carrier	Steel	Very relevant
	Electronics	Relevant
	Paints/resins	Moderately relevant
	Aluminium	Not very relevant
	Other	Marginal
LNG Carrier	Electronics	Very relevant
	Steel	Very relevant
	Aluminium	Very relevant
	Resins/plastics	Relevant

333 Ecoinvent Association. (2023). *Ecoinvent v3.9 Database*. https://www.ecoinvent.org
334 IRENA. (2021). *A pathway to decarbonise the shipping sector by 2050*. International Renewable Energy Agency.

	Cables/copper	Moderate
Ro-Ro / Pax Ferry	Aluminium	Very relevant
	Electronics	Very relevant
	Steel	Relevant
	Interior/plastics	Relevant
	Other composites	Moderate

Table 2 *– Summary of ship types and associated materials, with an analysis of the embedded relevance in terms of environmental impact and sustainability considerations*

Material	Oil Tanker (%)	Container Ship (%)	Bulk Carrier (%)	LNG Carrier (%)	Ro-Ro / Pax Ferry (%)	EF (kgCO2e/kg)	Oil Tanker - Embedded CO2e	Container Ship - Embedded CO2e	Bulk Carrier - Embedded CO2e	LNG Carrier - Embedded CO2e	Ro-Ro / Pax Ferry - Embedded CO2e
Steel	62	58	68	52	50	2	124	116	136	104	100
Aluminium	7	6	4	10	12	10	70	60	40	100	120
Electronics + wiring	11	14	9	18	16	15	165	210	135	270	240
Paints, resins, plastics	7	6	5	7	10	5	35	30	25	35	50
Other materials	13	16	14	13	12	3	39	48	42	39	36

Table 3 *– Summary of material composition and corresponding embedded CO_2e emissions across different ship types.*

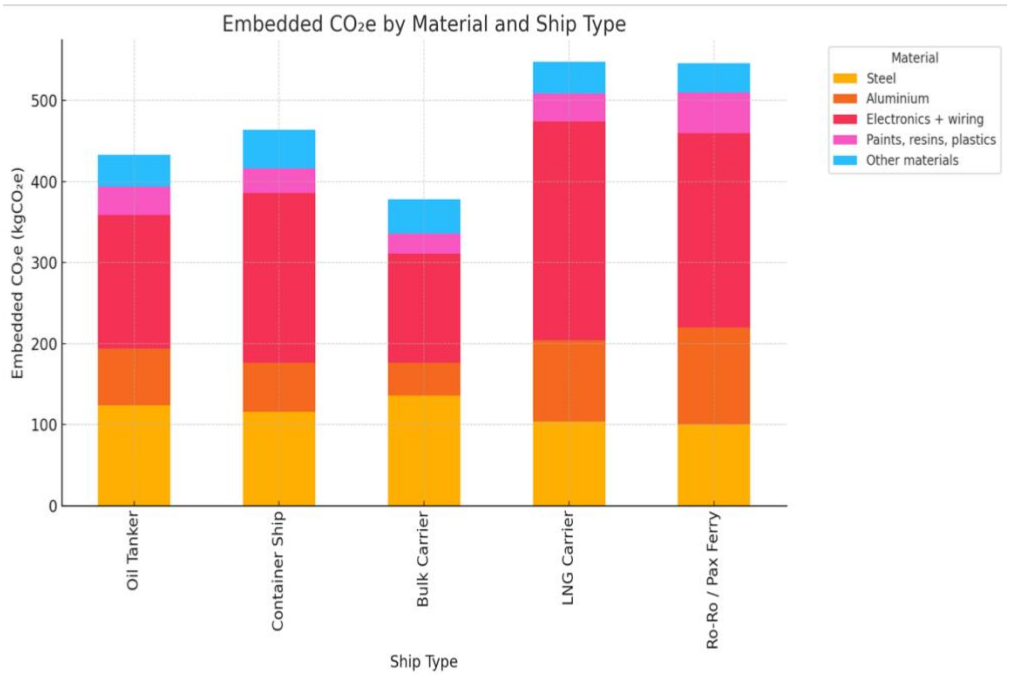

Chart 6 *– Breakdown of embedded CO_2e emissions by material and ship type.*

The stacked bar chart provides an integrated and comparative visualization of the embedded CO_2 emissions associated with construction materials across five representative ship types: Oil Tanker, Container Ship, Bulk Carrier, LNG Carrier, and Ro-Ro/Pax Ferry. The analysis is based on the combination of each material's mass share within the ship structure and its corresponding emission factor (EF), expressed in $kgCO_2e$ per kilogram of material, allowing for a detailed quantification of upstream environmental impact. The highest total embedded emissions are observed in LNG Carriers and Ro-Ro/Pax Ferries, both exceeding 540 $kgCO_2e$, while the Bulk Carrier shows the lowest total impact despite a substantial use of steel, due to the lower EF associated with this material. Steel remains the dominant structural material across all vessel types and contributes, on average, about one-quarter of the total embedded emissions; however, due to its relatively low EF, its contribution is primarily a function of mass[335]. In contrast, electronics and wiring, though minor in terms of weight, are the most carbon-intensive components due to their high EF (15 $kgCO_2e$/kg), and account for nearly 50% and 45% of total embedded emissions in LNG Carriers and Ro-Ro Ferries respectively, highlighting the high transition risk linked to technologically complex ships. Aluminium, increasingly used in passenger ferries to reduce weight and enhance energy efficiency, plays a significant role in the total upstream impact of Ro-Ro vessels, where it accounts for over 20% of emissions[336]. Materials such as paints, resins, and plastics—although often considered secondary—also contribute

[335] Global Maritime Forum. (2022). *2022 Annual Progress Report on Green Shipping Corridors*.
[336] IRENA. (2021). *A pathway to decarbonise the shipping sector by 2050*. International Renewable Energy Agency

significantly to passenger vessels, particularly ferries, due to their extensive use in interiors and coatings, with values reaching 50 $kgCO_2e$. The “other materials” category shows lower variability and impact but nonetheless contributes to the overall footprint[337]. A technical interpretation of the chart reveals that upstream carbon impact is not solely a function of ship type but is strongly influenced by the specific composition of materials and the traceability and sustainability of the supply chain. The presence of high-emission materials such as electronics and aluminium emphasizes the importance of strategic procurement choices and the integration of embedded carbon metrics into environmental risk assessment models, particularly within sustainable finance and ESG-oriented banking frameworks.

3.4.2. Upstream traceability and environmental impact analysis

To evaluate the upstream environmental footprint of ship construction in a rigorous and operationally relevant manner, a detailed environmental traceability profile has been developed for each critical material identified in the supply chain. These traceability data sheets are designed to capture the main variables that influence the embedded carbon intensity of materials and their associated sustainability risks[338]. Each profile includes key technical and environmental attributes such as the material's geographical origin and the dominant production technology adopted—for instance, whether steel is produced via blast furnace (BF) or electric arc furnace (EAF) processes. This distinction is critical, as it directly influences the level of Scope 1 and 2 emissions associated with the material’s primary production phase.

In addition to emissions data, the traceability framework evaluates the availability of low-impact alternatives—such as recycled aluminium, secondary metals, or bio-based polymers—capable of significantly reducing the upstream carbon intensity. Furthermore, it assesses the presence and robustness of recognized environmental certifications, including but not limited to EPD (Environmental Product Declarations)[339], ISO 14067 (Carbon Footprint of Products)[340], ASI (Aluminium Stewardship Initiative)[341], and RoHS (Restriction of Hazardous Substances)[342]. Each material is then subjected to a qualitative assessment of its transition risk, which reflects the likelihood

[337] Global Maritime Forum. (2022). *2022 Annual Progress Report on Green Shipping Corridors*.
[338] CIMAC. (2008). *Greenhouse gas emissions from ships – Reduction options and effects on climate*. CIMAC Technical Paper.
[339] The International EPD System. (2024). *Environmental product declarations (EPDs) in the construction sector*.
[340] International Organization for Standardization. (2018). *ISO 14067:2018 – Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification*. International Organization for Standardization.
[341] The Aluminium Stewardship Initiative (ASI). (2023). *ASI certification: Setting standards for responsible aluminium production*. Aluminium Stewardship Initiative.
[342] European Commission. (2022). *Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)*.

that future regulatory or market shifts (e.g., carbon pricing, green procurement standards) will penalize materials with high carbon intensity or poor traceability. To translate these environmental attributes into actionable financial insight, the model also introduces a creditworthiness criterion, tailored to the perspective of financial institutions, which integrates traceability, certification, and emissions data into a composite indicator to support green lending and ESG-aligned credit risk analysis. For example, steel produced in blast furnaces located in regions heavily dependent on fossil fuels—often referred to as "brown steel"—is associated with an emission factor typically ranging between 2.0 and 2.2 $kgCO_2e$ per kg. By contrast, "green steel" manufactured via electric arc furnaces powered by renewable electricity can reduce this figure to well below 1.0 $kgCO_2e$ per kg[343]. This differential not only reflects a lower environmental impact but also signals lower transition risk, making such materials more attractive from a sustainable finance perspective.

343 GasLog Partners LP. (2023). *Sustainability Report 2023.*

Material	Prevalent production	Scope 1+2 emissions	Sustainable alternatives	Relevant certifications[345]	Transition Risk	Criterion for the Bank
Steel	China, India, EU (BF blast furnace or EAF electric furnace)	2	Green steel electric furnace with renewable energy	EPD[346], ISO 14067[347], ResponsibleSteel[348]	High	Finance only certified EPD and EAF suppliers
Aluminium	China, Canada, Norway, Gulf	10	ASI certified secondary or hydroelectric aluminum	ASI,[349] ISO 14067	Medium-high	Prefer ASI or recycled secondary
Electronics and Wiring	China, Korea, EU, Malaysia	15	Recycled components, production with renewable energy	RoHS,[350] REACH[351], ISO 14001[352], EPEAT[353]	High	Full traceability, recycled content >30%
Resins/Paints/Plastic	USA, EU, India, Saudi Arabia	5	Bio-resins, water-based paints, biobased plastics	Blue Angel[354], EU Ecolabel, ISO 14025[355]	Medium-high	Use of certified bio-based or water-based paints
Plastics & Insulators	EU, USA, Asia	3	Recycled plastics, certified compostable materials	ISCC+[356], Cradle-to-Cradle[357], EU Ecolabel[358]	Medium	Request certified circular or biodegradable plastic

Table 4 – Summary of material categories, carbon footprint data, sustainable alternatives, relevant certifications, and associated transition risks. The table provides an overview of recommended banking criteria for integrating climate considerations into lending decisions in the maritime sector.

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344 GasLog Partners LP. (2023). *Sustainability Report 2023.*
345 ResponsibleSteel. (2022). *Standard V2.1 – Certification of steel sites*
346 Environmental Product Declarations (EPD International). *EPD database*.
347 ISO. (2020). *ISO 14067: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification*. International Organization for Standardization.
348 ResponsibleSteel. (2022). *Standard V2.1 – Certification of steel sites*.
349 Aluminium Stewardship Initiative (ASI). (2021). *Performance Standard V3*
350 European Parliament & Council of the European Union. (2011). *Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS).* Official Journal of the European Union, L 174, 1–88.
351 European Parliament & Council of the European Union. (2006). *Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH).* Official Journal of the European Union, L 396, 1–849.
352 International Organization for Standardization. (2015). *ISO 14001:2015 – Environmental management systems – Requirements with guidance for use*. ISO.
353 Global Electronics Council. *EPEAT – The Global Electronics Council Registry*.
354 Umweltbundesamt. *Blue Angel – The German Ecolabel*.
355 International Organization for Standardization. (2006). *ISO 14025:2006 – Environmental labels and declarations – Type III environmental declarations – Principles and procedures*. ISO.
356 ISCC System GmbH. (n.d.). *ISCC PLUS – Certification for the Circular Economy and Bioeconomy*.
357 Cradle to Cradle Products Innovation Institute. (2021). *Cradle to Cradle Certified® Product Standard Version 4.0*.
358 European Parliament & Council of the European Union. (2010). *Regulation (EC) No 66/2010 on the EU Ecolabel*. Official Journal of the European Union, L 27, 1–19.

3.4.3. Construction of an ESG scoring model for materials

Building upon the previously developed environmental traceability profiles, a simplified ESG scoring model was designed to evaluate the upstream sustainability of critical materials used in ship construction. The aim of this model is to provide a standardized, objective, and comparable tool for assessing the environmental performance of materials based on supply chain quality, circularity, and exposure to transition risk. Each material is assigned an ESG score ranging from 0 to 1, calculated as the simple arithmetic average of five key environmental indicators that reflect both the material's intrinsic sustainability and the robustness of its supply chain.

The five scoring criteria are as follows:

1. Certified origin: measures the presence of internationally recognized environmental certifications (e.g., EPD, ASI, ISO 14067). A score of 1 is given for full certification, 0.5 for partial, and 0 for none.
2. Production with renewable energy evaluates whether the material's production process uses electricity from renewable sources.
3. Recycled content: estimates the share of recycled or secondary raw material used in production. Full score is granted if ≥50%, partial if 10–49%, and zero if <10%.
4. Supply chain traceability indicates the availability and quality of verifiable data on the material's origin and production process.
5. Transition risk (reverse): reflects the likelihood that the material will be affected by future regulatory, market, or environmental risks. A low-risk profile scores 1, medium risk 0.5, and high risk 0.

Material	Certified origin (EPD/ASI/etc.)	Production with renewables	Presence of recycled content	Supply chain traceability	Transition risk (reverse)	ESG score (0–1)
Steel	1	1	0,5	1	1	0,9
Aluminium	1	1	1	1	0,8	0,96
Electronics/Wiring	0,5	0	0,5	0,5	0,6	0,42
Resins/Paints	0,5	0,5	0,5	0,5	0,6	0,52
Plastics/Composites	0,5	0,5	1	0,5	0,7	0,64

Table 5 – Comparative evaluation of materials based on key sustainability criteria

Calculation method

To ensure consistency and comparability across different material categories, the ESG score for each material is calculated using a simple arithmetic average of the five individual subscores that represent the selected environmental criteria. These criteria—certified origin, renewable energy usage, recycled content, supply chain traceability, and transition risk—are each assigned a score ranging from 0 to 1 based on standardized thresholds. The overall ESG score is then computed using the following formula:

$$\text{ESG Score (material)} = \frac{\sum_{i=1}^{5} \text{score}_i}{5}$$

In this formula, score (i)represents the value attributed to each of the five environmental dimensions. The final ESG score thus reflects the average performance of a material across all criteria, with higher values indicating greater alignment with sustainability objectives and lower transition risk.

To illustrate, consider the case of a given type of steel with the following characteristics:

- It possesses a full Environmental Product Declaration (EPD): 1
- It is produced using electricity from renewable sources: 1
- It contains 10–49% recycled material: 0.5
- The supply chain is fully traceable: 1
- It is considered to have a low transition risk: 1

Applying the formula, the ESG score is calculated as:

$$\frac{1 + 1 + 0.5 + 1 + 1}{5} = 0.9$$

This ESG score, expressed on a continuous scale from 0 to 1, serves as a synthetic proxy for the upstream environmental sustainability of the material. It can be directly integrated into credit risk assessment models or ESG screening tools employed by financial institutions, providing a data-driven basis for green lending decisions, project evaluations, and alignment with regulatory frameworks such as the EU Taxonomy.

3.4.4. Extension of the model to the different types of ships

The ESG scoring model was extended to different ship types by applying the material composition percentages specific to each vessel class and combining them with the previously calculated ESG scores of individual materials. This cross-referencing produced a weighted average ESG score for each ship, offering a quantitative measure of the upstream environmental quality of its construction supply chain. The results of this analysis are summarized in the following table:

Ship Type	ESG score (0–1)
Oil Tanker	0.802
Container Ship	0.781
Bulk Carrier	0.800
LNG Carrier	0.796
Ro-Ro / Pax Ferry	0.803

***Table 6** – ESG scores assigned to different ship types, representing the degree of sustainability and climate resilience embedded in each ship type.*

The data clearly demonstrate that the quality of the material supply chain plays a more decisive role in determining ESG performance than the functional or operational category of the ship itself. For instance, LNG Carriers—despite having the highest share of electronics, which are among the most carbon-intensive components—achieve a strong ESG score (0.796) when built using certified, traceable, and low-impact materials. Similarly, Ro-Ro / Pax Ferries obtain the highest score (0.803), even though they employ significant amounts of high-EF materials such as aluminium and polymers, thanks to the use of suppliers aligned with sustainability criteria and circular economy principles. These findings highlight the fact that procurement strategy and supplier selection are critical determinants of a vessel's upstream sustainability profile[359]. From the perspective of financial institutions, this underscores the importance of incorporating ESG performance and traceability into creditworthiness assessments and project screening tools, in alignment with the EU Taxonomy and broader sustainable finance frameworks.

3.4.5. Implications for sustainable finance and banking governance

The integration of upstream embedded carbon analysis into the evaluation of shipbuilding projects represents a strategic and forward-looking tool for financial institutions. By quantifying the carbon intensity of materials used during the construction phase—well before the vessel enters operation—this approach enables the early identification of transition risks linked to evolving regulations, market dynamics, and reputational exposure. It provides banks with a robust and objective foundation for

[359] Cheniere Energy. (2021). *Supplier-specific life-cycle assessment of LNG supply chains*. Nicholas Institute at Duke University.

assessing the environmental consistency of the shipowner's procurement decisions, extending the analysis beyond the operational performance of the asset to include the quality, traceability, and sustainability of the underlying supply chain.

This methodology also significantly enhances the financial sector's ability to verify project alignment with the EU Taxonomy, particularly in relation to the technical screening criteria applied to carbon-intensive industrial sectors such as shipbuilding. Through the adoption of standardized ESG scores and traceability indicators, the model supports compliance with emerging disclosure obligations introduced by the Corporate Sustainability Reporting Directive (CSRD) and other sustainable finance regulations.

A further implication of this approach lies in its capacity to support differentiated credit strategies. Financial institutions may reward projects that demonstrate higher environmental integrity and supply chain transparency—such as those using certified low-impact materials or ESG-compliant suppliers—by offering preferential terms. These projects may qualify for innovative financial instruments including ESG-linked loans, climate-aligned project finance, or sustainability-adjusted interest rates.

Although the model is intentionally simplified, it is built upon a solid methodological framework that aligns with the principles of technical ESG due diligence. Unlike traditional life-cycle assessments (LCAs), which focus primarily on operational emissions, this model acts upstream, influencing material selection and supplier engagement from the outset. In this respect, it functions not merely as a measurement tool, but as a governance mechanism for sustainable finance, capable of informing strategic and allocative decisions within a rapidly evolving regulatory and market landscape.

Its streamlined structure also represents a practical advantage: due to the standardization of criteria and its methodological clarity, the model is easily integrable into financial decision-making processes. It serves as a preliminary but concrete tool for identifying environmentally low-risk projects, enhancing credit analysis with verifiable ESG elements, and directing capital flows toward more sustainable and traceable production chains. Furthermore, its modular architecture makes it inherently scalable and adaptable: it can be progressively refined through the inclusion of more granular indicators, sector-specific benchmarks, or advanced financial metrics, thus evolving from a simplified assessment framework into a dynamic technical-financial scoring system. Looking ahead, this positions the model not only as a tool for the maritime sector, but as a replicable standard for upstream sustainability evaluation across a wide range of industrial contexts.

Chapter 4 – Transition Metrics and KPIs Applicable to the Maritime Industry

4.1. General and ship-specific environmental metrics

The growing regulatory, financial and social pressure towards the decarbonisation of the maritime sector has made it necessary to adopt standardised environmental metrics, posing new challenges for shipping companies, financial institutions and regulatory authorities.

Key Performance Indicators (KPIs) are emerging as fundamental tools for measuring, assessing and improving the operational and environmental performance of ships and indirectly the achievement of targets by lenders and investors financing the sector. KPIs not only provide objective metrics for performance monitoring but can also serve as decision-support tools for investors and financial stakeholders, influencing access to finance and accelerating the energy transition of the sector.

Recent literature has increasingly emphasized the strategic role of Key Performance Indicators (KPIs) in assessing and managing multiple dimensions of ESG performance across various industrial sectors, including maritime transport[360]. In the shipping industry, KPIs are particularly relevant as they provide quantifiable metrics to evaluate environmental impacts, operational efficiency, and alignment with sustainability goals, thus supporting both regulatory compliance and investment decision-making.

Sustainability KPIs for the shipping sector can be divided into different categories[361], depending on the specific measurement area. The most relevant are those related to greenhouse gas emissions, which include indicators such as CO2 Emission Intensity, which measures carbon dioxide emissions per tonne-mile transported, and the Carbon Intensity Indicator (CII), introduced by the IMO to assess the operational efficiency of ships in terms of CO_2 emissions in relation to transport capacity and distance travelled. Similarly, the monitoring of sulphur oxides (SOx) and nitrogen (NOx) emissions can be used to assess the level of air pollution generated by marine fuels, providing a key parameter for the adoption of solutions with lower environmental impact.

In addition to emission indicators, KPIs related to energy efficiency are of particular importance, as they are crucial for determining the relationship between fuel consumption and operational capacity of the ship. The main reference in this area is the Energy Efficiency Operational Indicator (EEOI), which allows to quantify the overall efficiency of the ship based on the fuel consumed per tonne-mile

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[360] Yip, A. W., & Yu, W. Y. (2023). The quality of environmental KPI disclosure in ESG reporting for SMEs in Hong Kong. *Sustainability, 15*(13), 10021.

[361] Wijayanto, D. (2020). *The development of an operational KPI for energy efficiency ship operation* (Master's dissertation, World Maritime University). The Maritime Commons.

of transport. Together with the EEOI, the Energy Efficiency Existing Ship Index (EEXI) measures the energy efficiency of existing ships, while the Fuel Consumption KPI provides a detailed indication of the fuel consumption in relation to the distance travelled and the cargo carried.
Danuja Wijayanto's research the World Maritime University bears relevance in this respect[362]. This work focuses on the development of an operational Key Performance Indicator (KPI) to measure the energy efficiency of ships. By considering the growing attention to CO2 emissions and international environmental regulations, such as the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI), it develops a standardized and effective methodology for measuring the environmental impact of maritime operations increasingly necessary. However, traditional methods of assessing energy efficiency are often insufficient because they are based on theoretical models and limited data collected under ideal operating conditions that do not reflect the complex reality of global navigation. The contribution proposes a KPI that can integrate the actual operational data of a ship, including fuel consumption, average speed and cargo carried, to obtain a more precise picture useful for operators in the sector. The suggested approach is based on a combination of key parameters, including the Energy Efficiency Operational Indicator (EEOI), the Fuel Consumption KPI and the Main Engine Fuel Consumption KPI, With the aim of providing an objective benchmark to compare the performance of different vessels and optimize energy management strategies. One of the most interesting aspects of the research is the difficulty in implementing such KPIs at an operational level. Wijayanto points out that the poor quality of data collected on board, the lack of standardization between different shipping companies and the difficulty in adapting existing metrics to a variety of ship types represent significant obstacles to the large-scale adoption of an operational KPI for energy efficiency. Regulatory and financial incentives are also needed to encourage the maritime industry to invest in more advanced monitoring tools and more sustainable technologies. This research is closely linked to the theme of energy transition in the shipping sector. If alternative fuels are to become a credible solution for reducing emissions, they must demonstrate measurable efficiency through reliable indicators such as those proposed by Wijayanto. Another crucial aspect is the adoption of alternative fuels, an increasingly relevant issue for decarbonization in the shipping sector. The Alternative Fuel Use KPI allows to estimate the percentage of energy derived from less polluting fuels, such as liquefied natural gas (LNG), ammonia, methanol and hydrogen, The Renewable Energy Integration KPI measures the degree of adoption of renewable sources such as automatic sails, batteries and solar panels. Finally, a key component of sustainability in the maritime sector is the

[362] Wijayanto, D. (2020). *The development of an operational KPI for energy efficiency ship operation* (Master's dissertation, World Maritime University). The Maritime Commons.

management of the overall environmental impact of the ship, through indicators such as the Ship Recycling KPI, which monitors compliance with sustainable recycling standards, and the Port Efficiency KPI, which evaluates the efficiency of port operations to reduce downtime and energy consumption. The systematic adoption of these KPIs provides a solid basis for assessing and improving the sustainability of maritime operations, while facilitating access to financing and incentives related to green transition. Wijayanto (2020) also praises the importance of integrating KPIs in financial valuation processes, stressing the possibility of having fundamental criteria for banking institutions when granting loans to shipping companies, thus promoting more targeted investment towards a decarbonization of the sector.

A further methodological refinement was carried out through the review of the most recent guidelines and international frameworks published by leading institutions such as the Climate Bonds Initiative (CBI)[363], the Transition Plan Taskforce (TPT)[364], the ACT initiative (Assessing Low-Carbon Transition)[365], and the ATP-Col collective (Assessing Transition Plans Collective)[366]. In particular, the CBI Shipping Criteria represent a key technical standard for the certification of green bonds in the maritime sector, offering clear sectoral benchmarks for assessing the environmental performance of vessels. The TPT framework, published in 2023, provides a solid structure for the disclosure of transition plans, with an emphasis on reporting targets, milestones, and performance indicators, while the ACT Framework version 2.0 (2024) proposes an assessment methodology grounded in operational evidence and aligned with decarbonization scenarios. Finally, the ATP-Col guidance focuses on evaluating the credibility of corporate transition plans, suggesting qualitative and quantitative criteria for comparative analysis and internal consistency of the KPIs adopted.

The integration of these sources has enabled a refinement of Wijayanto's (2020) analysis[367], offering a more concrete and updated view of the relevant environmental metrics in the shipping sector. The KPIs recommended by these frameworks not only reaffirm the importance of parameters such as EEOI, EEXI, and CII, but also broaden their significance within the context of a sustainable transition, highlighting the need for reliable and transparent indicators, particularly for financial disclosure and access to credit. The use of these guidelines has substantially contributed to our research by ensuring

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[363] Climate Bonds Initiative. (2020, October). *Shipping criteria under the Climate Bonds Standard*.
[364] Transition Plan Taskforce. (2023, October). *TPT disclosure framework*. HM Treasury.
[365] ADEME & CDP. (2024, November). *ACT framework version 2.0: Assessing low-carbon transition*.
[366] Assessing Transition Plans Collective. (2024, September). *Assessing the credibility of a company's transition plan: Framework and guidance*. World Benchmarking Alliance.
[367] Wijayanto, D. (2020). *The development of an operational KPI for energy efficiency ship operation* (Master's dissertation, World Maritime University). The Maritime Commons.

methodological rigor, regulatory relevance, and alignment with the expectations of institutional investors and supervisory authorities.

EEDI – Energy Efficiency Design Index

The Energy Efficiency Design Index (EEDI) is the key metric introduced by the International Maritime Organization (IMO) to assess the energy efficiency of ships at the design stage. Officially established under MARPOL Annex VI, Chapter 4, Regulation 21[368], the EEDI became mandatory on January 1st, 2013 for newly built vessels falling within specific size and type categories. This index is expressed in grams of carbon dioxide (CO_2) per tonne-nautical mile (g CO_2/ton-nm) and quantifies the expected emissions per unit of cargo transported over one nautical mile, based on the ship's technical design characteristics.

The EEDI is calculated using the following basic formula**:**

$$\text{EEDI} = \frac{(C_F \cdot SFC \cdot P_{ME}) + (C_F \cdot SFC \cdot P_{AE})}{\text{Capacity} \cdot V_{ref}}$$

Where:

- C_F is the **fuel conversion factor**, expressed in grams of CO_2 per gram of fuel (g CO_2/g fuel), and varies depending on the type of fuel used (e.g., HFO, MGO, LNG);
- SFC stands for **Specific Fuel Consumption**, measured in grams per kilowatt-hour (g/kWh);
- P_{ME} and P_{AE} represent the **main engine** and **auxiliary engine power**, respectively, expressed in kilowatts (kW);
- **Capacity** refers to the **cargo-carrying capacity** of the vessel, expressed in deadweight tonnage (DWT) or gross tonnage (GT), depending on ship type;
- V_{ref} is the **reference speed** of the vessel in knots (kn), determined according to standardized test procedures.

The EEDI serves a dual purpose. On the one hand, it acts as a design benchmark, enabling comparisons between vessels of the same category in terms of expected energy efficiency. On the other, it functions as a regulatory instrument within a progressively tightening framework. The IMO has established increasingly stringent EEDI reduction phases (Phases 0, 1, 2, and 3), each imposing lower CO_2 intensity limits, thereby incentivizing continuous improvements in ship design to reduce greenhouse gas emissions[369].

From an innovation standpoint, the EEDI has been instrumental in driving the development and adoption of more efficient technologies, such as hydrodynamically optimized hulls, air lubrication

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[368] International Maritime Organization. (2013). *MARPOL Annex VI, Chapter 4 – Energy Efficiency Regulations*
[369] International Maritime Organization. *MARPOL Annex VI – Prevention of Air Pollution from Ships*.

systems, LNG-fuelled propulsion, dual-fuel engines, and waste heat recovery systems. It is therefore a core technical lever in the decarbonization of the shipbuilding sector.

However, the EEDI also presents inherent limitations. As a static design metric, it does not account for a vessel's actual performance in operation, nor does it incorporate dynamic variables such as cargo utilization, sea and weather conditions, or routing behaviour. Moreover, it does not consider operational strategies like slow steaming or voyage optimization. As such, while the EEDI provides a valuable regulatory foundation, it must be complemented by operational metrics—notably the EEOI and the CII—to gain a comprehensive view of a vessel's environmental performance throughout its life cycle.

EEOI – Energy Efficiency Operational Indicator

The Energy Efficiency Operational Indicator (EEOI) is a voluntary metric recommended by the International Maritime Organization (IMO) through the MEPC.1/Circ.684 guidelines[370], aimed at measuring the actual operational energy efficiency of a vessel. Unlike design-based indicators such as the EEDI, the EEOI evaluates the ship's performance in real-life navigation scenarios, incorporating actual fuel consumption and transported cargo data. It is expressed in grams of CO_2 emitted per tonne of cargo per nautical mile (g CO_2/ton-nm), providing a dynamic and voyage-specific measure of carbon intensity.

The EEOI is calculated using the following standard formula:

$$\text{EEOI} = \frac{\sum_i (FC_i \cdot C_{F_i})}{\sum_j (m_{cargo,j} \cdot D_j)}$$

Where:

- FC_i denotes the **fuel consumption** during voyage i, measured in metric tons or kilograms;
- C_{F_i} is the **CO_2 emission factor** of the fuel used during voyage i, expressed in g CO_2/g fuel, and determined by the fuel type (e.g., HFO, MDO, LNG);
- $m_{cargo,j}$ indicates the **mass of cargo transported** during voyage j, expressed in metric tons;
- D_j represents the **distance travelled** during voyage j, expressed in nautical miles.

The EEOI allows for a continuous monitoring of operational performance and is particularly useful in identifying opportunities for improving voyage efficiency. For example, by analyzing EEOI trends, ship operators can evaluate the impact of slow steaming strategies, weather routing optimization, or

[370] International Maritime Organization. (2009). *MEPC.1/Circ.684: Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI)*

load factor improvements. This makes the EEOI a valuable internal management tool that can drive energy-saving decisions and reduce greenhouse gas (GHG) emissions over time.
One of the key strengths of the EEOI lies in its ability to reflect real-time variability in ship operations, making it highly responsive to both technical and managerial adjustments[371]. However, this same flexibility introduces certain limitations. The accuracy and reliability of the EEOI heavily depend on the quality and consistency of input data, particularly regarding fuel measurements, voyage distances, and cargo mass declarations. Additionally, the indicator's comparability across vessel types is limited, as operational profiles vary significantly between segments (e.g., tankers vs. containerships), necessitating normalization or categorization for meaningful benchmarking.
Despite these constraints, the EEOI remains an important tool for understanding and managing the environmental footprint of maritime operations. Its voluntary nature provides companies with the flexibility to implement it as part of broader energy efficiency management systems (SEEMP) or corporate ESG monitoring frameworks, supporting internal decision-making and external disclosure alike.

CII – Carbon Intensity Indicator

The Carbon Intensity Indicator (CII) is a regulatory metric introduced by the International Maritime Organization (IMO) to measure the annual carbon intensity of ships. It became mandatory in 2023 for all vessels exceeding 5,000 gross tonnages (GT), as established under MARPOL Annex VI, Regulation 26[372]. The CII quantifies the grams of CO_2 emitted per deadweight ton per nautical mile (g CO_2/dwt-nm) over the course of a calendar year and assigns a performance rating ranging from A (highest) to E (lowest), which is updated annually[373]. The first year of operational verification of the CII was 2024, based on performance data recorded during the 2023 calendar year. From that point onward, each vessel receives an environmental performance rating according to the following scale:

- A: excellent superior performance
- B: above-average performance
- C: minimum required compliance level
- D: below-standard performance
- E: significantly inadequate performance

Ships receiving a D or E rating for three consecutive years are required to develop and implement a Corrective Action Plan, which must be integrated into SEEMP Part III (Ship Energy Efficiency

[371] DNV. *EEOI Certification*.
[372] International Maritime Organization. *Index of MEPC Resolutions and Guidelines Related to MARPOL Annex VI.*
[373] https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/

Management Plan) and is subject to audit and verification by the flag administration or a recognized organization.

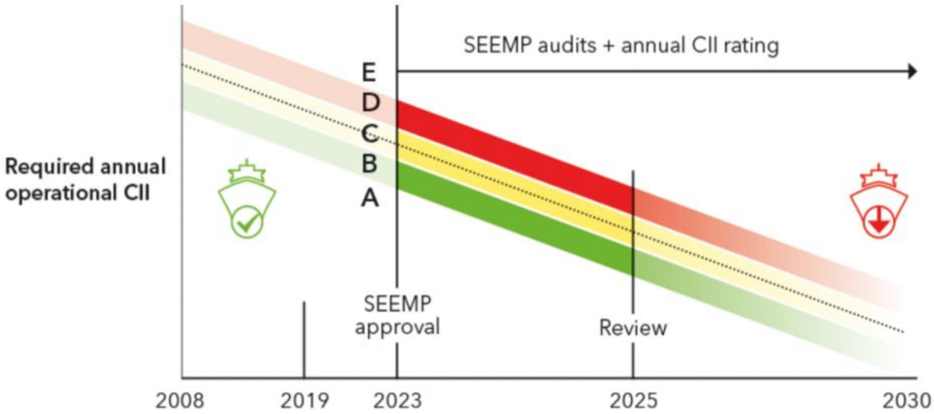

Chart 7. The timeline for the implementation of the Carbon Intensity Indicator (CII) in the maritime sector.

As shown in the figure, the CII rating thresholds will become progressively stricter through to 2030, encouraging shipping companies to continuously improve their environmental performance.
The simplified formula used to calculate the CII is as follows:

$$\text{CII} = \frac{\text{Annual CO}_2 \text{ emissions (g)}}{\text{Deadweight (DWT)} \cdot \text{Distance sailed (nautical miles)}}$$

Where:

- **Annual CO_2 emissions** refer to the total amount of carbon dioxide emitted by the ship over a one-year period, based on fuel consumption data;
- **Deadweight (DWT)** is the carrying capacity of the ship in metric tons;
- **Distance sailed** corresponds to the total nautical miles covered during the year.

The CII rating is a key feature of the IMO's revised decarbonization strategy. Ships that receive a D or E rating for three consecutive years are required to implement a mandatory corrective action plan, integrated into the Ship Energy Efficiency Management Plan (SEEMP). This plan must outline the measures the shipowner intends to adopt to restore compliance with the established intensity thresholds[374].
From a strategic perspective, the CII functions as a regulatory pressure mechanism, signalling to shipowners, charterers, insurers, and financial institutions the level of environmental performance of a given asset. Soon, it is expected that vessels with persistently low ratings (C, D, or E) may face

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[374] Lloyd's Register. (2022). *MARPOL Annex VI – SEEMP Part III and Carbon Intensity Indicator (CII).*

restricted access to financing, higher insurance premiums, or exclusion from charter agreements, thereby accelerating the phasing out of inefficient tonnage.

Moreover, the CII provides a medium-term planning horizon for shipowners seeking to invest in retrofit solutions (such as engine upgrades, hull modifications, or alternative fuel systems) or in the replacement of underperforming assets with new, compliant tonnage. While the CII introduces a relatively simple metric, it acts as a powerful incentive for the maritime industry to progressively align its operations with international climate goals.

EEXI - Energy Efficiency Existing Ship Index

The Energy Efficiency Existing Ship Index (EEXI) is a regulatory mechanism introduced by the International Maritime Organization (IMO) under MARPOL Annex VI, designed to extend energy efficiency requirements to the existing fleet, i.e., vessels already in service that are not subject to the Energy Efficiency Design Index (EEDI). The EEXI came into effect on 1 January 2023 and applies to all ships above 400 gross tonnages (GT) falling within the relevant regulatory categories[375].

Similar in structure to the EEDI, the EEXI measures the design energy efficiency of a vessel, expressed in grams of CO_2 emitted per tonne-nautical mile (g CO_2/ton-nm). It is, however, applied retroactively to ships already in operation, using existing technical specifications rather than real-time operational data. The EEXI is a one-time technical assessment designed to verify whether a ship meets the minimum efficiency thresholds set for its class and size category. The calculation methodology is based on the same formula as the EEDI, adapted to reflect the current configuration of the ship, including installed engine power, specific fuel consumption, fuel type, and reference speed.

From an operational standpoint, the EEXI serves as a preliminary compliance requirement, ensuring that all ships meet a baseline level of design efficiency before they are subject to ongoing performance monitoring. Non-compliant vessels must implement corrective technical measures to bring their EEXI value within acceptable limits. These typically include Engine Power Limitation (EPL), hull form optimization, or the integration of energy-saving devices aimed at reducing hydrodynamic resistance or improving combustion efficiency.

Within the broader regulatory framework, the EEXI complements the EEDI and CII, forming a three-tiered structure for maritime decarbonization:

- The EEDI applies to newbuilds, mandating high design efficiency from the outset.

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[375] https://www.dnv.com/maritime/insights/topics/eexi/

- The EEXI addresses existing ships, enforcing a one-time design efficiency check based on their technical profile.
- The CII evaluates ships on an annual operational basis, using real-world emissions data to determine performance.

This sequence ensures full lifecycle coverage of energy efficiency regulation, from vessel design and retrofitting to day-to-day operational management.

Among its main advantages, the EEXI serves to level the regulatory playing field by requiring older vessels to conform to minimum energy efficiency standards, thereby narrowing the performance gap between existing and new ships. It also acts as a catalyst for technical upgrades and retrofits, many of which are cost-effective and can be implemented without major design overhauls.

Nonetheless, the EEXI presents structural limitations. Being a static, design-based index, it does not reflect a vessel's real-world operating conditions or behavioural variables such as loading patterns or voyage speeds. Moreover, it is a one-time compliance measure and thus does not incentivize continuous improvement—a function carried out instead by the CII. Finally, the EEXI does not account for fuel life-cycle emissions (well-to-wake), focusing solely on onboard combustion (tank-to-wake) CO_2 emissions.

In conclusion, the EEXI represents a foundational element in the IMO's decarbonization strategy, ensuring that the global fleet aligns with a universal minimum standard of design efficiency, while serving as the technical entry point for more advanced, performance-based tools such as the CII.

gCO_2/ton-mile:

The gCO_2/ton-mile metric, also referred to as grams of CO_2 per tonne-nautical mile, is a standard measure of emissions intensity in maritime transport. It quantifies the amount of carbon dioxide emitted for each tonne of cargo transported over one nautical mile, offering a straightforward way to assess the carbon performance of shipping activities. While in some contexts it may align closely with more comprehensive indicators such as the Energy Efficiency Operational Indicator (EEOI) or the Carbon Intensity Indicator (CII), the gCO_2/ton-mile metric stands out for its conceptual simplicity and broad applicability.

This indicator plays a particularly valuable role in enabling cross-sectoral comparisons of transport emissions. For example, it facilitates the comparison of maritime freight with other modes of transport such as rail, road, or aviation, by offering a common denominator in terms of emissions per unit of transported mass and distance. This makes it especially useful in policy analysis, modal shift evaluations, and supply chain optimization strategies aimed at reducing overall logistics emissions.

Moreover, the gCO_2/ton-mile metric is frequently employed in well-to-wake (WTW) lifecycle assessments, which consider the full spectrum of emissions—from fuel extraction and production to combustion onboard. In this context, the metric serves as a core component of environmental impact calculations for various fuel types and propulsion systems, including conventional fossil fuels and emerging low-carbon alternatives.

Although it lacks the operational specificity and regulatory enforcement mechanisms of the EEOI or CII, the gCO_2/ton-mile remains a reliable and versatile benchmark, particularly for high-level evaluations of carbon intensity across fleets, transport corridors, or logistical chains. Its consistent use supports transparency, comparability, and alignment with decarbonization targets in global transport reporting frameworks.

SFC (Specific Fuel Consumption):

The Specific Fuel Consumption (SFC) is a key technical indicator used to evaluate the thermodynamic efficiency of marine engines. It represents the amount of fuel required to produce one kilowatt-hour (kWh) of useful energy output and is typically expressed in grams per kilowatt-hour (g/kWh). This metric is essential for comparing different engine types, assessing fuel economy, and determining the energy performance of onboard propulsion systems[376].

The SFC is most often calculated under standardized test conditions provided by engine manufacturers, but it can also be measured during actual operations to evaluate real-world performance. In general, two-stroke marine diesel engines—commonly used in large ocean-going vessels—tend to exhibit lower SFC values (e.g., 170–190 g/kWh) compared to four-stroke engines, which are typical in smaller vessels or auxiliary systems and may consume between 190–220 g/kWh[377].

This metric is particularly useful when analysing the cost-effectiveness of fuel switching (e.g., from heavy fuel oil to liquefied natural gas), or the return on investment of engine retrofitting, hybridization, or waste heat recovery technologies. It also plays a role in the evaluation of alternative propulsion systems, such as dual-fuel engines or fuel cells.

However, the SFC is sensitive to operational variables such as engine load, maintenance status, ambient conditions, and fuel quality. A lower SFC does not automatically imply lower total emissions, especially if the engine operates outside optimal conditions. Therefore, while SFC provides critical

[376] Marques, C. H., Caprace, J.-D., Belchior, C. R. P., & Martini, A. (2019). An Approach for Predicting the Specific Fuel Consumption of Dual-Fuel Two-Stroke Marine Engines. *Journal of Marine Science and Engineering*, 7(2), 20.

[377] ScienceDirect. *Specific Fuel Consumption – An Overview*

insights into fuel efficiency at the unit level, it must be interpreted within the broader context of vessel operations and energy management strategies.

Percentage of Alternative Fuel Used:

The percentage of alternative fuel used is an emerging key performance indicator that reflects the extent of decarbonization efforts in the shipping industry. It measures the share of a vessel's total fuel consumption—either by volume, mass, or energy content—that is derived from low-carbon or zero-carbon energy sources, such as liquefied natural gas (LNG), green methanol, ammonia, hydrogen, biofuels, or synthetic e-fuels.

This metric is gaining increasing relevance in environmental reporting frameworks, green finance mechanisms, and regulatory discussions, as it directly illustrates the shift away from traditional fossil fuels. When applied consistently, it provides insight into how rapidly and effectively shipping companies are embracing fuel-switching strategies to meet long-term climate goals[378].

The indicator can be expressed using the following general formula:

$$\%\text{Alternative Fuel Used} = \left(\frac{\text{Volume or Energy Content of Alternative Fuels}}{\text{Total Fuel Consumption}}\right) \times 100$$

A high percentage signals proactive alignment with decarbonization pathways, such as those set by the IMO GHG Strategy, the EU Emissions Trading System, or voluntary initiatives like the Poseidon Principles. In the context of maritime finance, this metric is increasingly viewed as a proxy for a vessel's climate alignment score and its access to sustainable funding mechanisms.

Nevertheless, the widespread adoption of alternative fuels faces several practical challenges, including fuel availability, port bunkering infrastructure, certification standards, and engine compatibility. Moreover, the true environmental benefit of these fuels depends on their well-to-wake carbon intensity—for example, LNG may reduce CO_2 emissions at the exhaust but may also lead to methane slip, undermining climate gains[379].

Despite these complexities, tracking the percentage of alternative fuels used remains a critical metric for assessing the pace of technological and operational transition in the shipping sector, and for ensuring transparency in environmental performance reporting.

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[378] International Maritime Organization. *IMO's Work to Cut GHG Emissions from Ships*.

[379] Reuters. (2024, November 28). *Maersk could use 15-20% alternative fuels for its fleet in 2030*.

4.2. Ship Type Specific KPI

The effectiveness of sustainability KPIs for the shipping sector depends largely on their ability to adapt to different ship types and operational specificities of each maritime transport sector. The variability of ship sizes, routes and functions requires the adoption of indicators that can more accurately reflect their environmental and operational performance. In the case of cargo and container ships, which are the main means of transport for goods globally, KPIs should consider the efficiency in the use of cargo space, the speed of navigation and fuel consumption on long-distance routes. One of the most significant parameters in this area is the Container Utilization KPI, which measures the capacity to optimize the load to reduce empty journeys and improve overall energy efficiency. In addition, indicators linked to the CII and EEOI are essential for assessing the environmental performance of cargo ships and comparing them with international benchmarks.

A study conducted by the Baltic and International Maritime Council (BIMCO) "Shipping KPI Standard" (2018)[380], proposes a global framework for benchmarking the performance of ships, with particular attention to environmental, technical and operational indicators. This study analyses a ship operational performance measurement system developed by the Baltic and International Maritime Council (BIMCO), the largest international body in the sector. The author points out that the increasing complexity of the maritime market, combined with the challenges of sustainability and safety, has made it essential to adopt a standardized system for benchmarking performance. The BIMCO KPI System is based on a series of key indicators covering different areas of ship management, including the Environmental Performance KPI, which measures the environmental impact of maritime operations, the Technical Performance KPI, which monitors the maintenance and reliability of ships, and the Operational Performance KPI, which assesses the efficiency of commercial operations. The aim of this system is to provide a benchmarking tool which enables shipping companies to monitor their performance against global standards and identify areas for improvement. One crucial aspect of the work is the need for greater integration between environmental KPIs and maritime finance strategies. If banks adopt the BIMCO KPI System as a reference to assess the sustainability of ships, companies would be encouraged to improve their energy efficiency to obtain better conditions for access to credit. In the case of tankers (tankers) and bulk carriers, which respectively transport liquids and loose materials such as coal, minerals and cereals, there are specific requirements related to cargo management and environmental safety. A central feature for tankers is the Cargo Heating Efficiency KPI, which measures the energy

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[380] Baltic and International Maritime Council (BIMCO). (2018). *Shipping KPI standard*.

consumption related to the heating of the load, an operation indispensable for the transport of oil and chemicals. Another crucial element is the Ballast Water Management KPI, which monitors compliance with international regulations on ballast water management, reducing the risk of alteration of marine ecosystems. Cruise ships and ferries, on the other hand, require KPIs that focus on managing energy and onboard resources, as they must ensure high standards of comfort for passengers without compromising environmental sustainability. In this context, the Energy Efficiency for Passenger KPI is an essential parameter to optimize energy consumption and improve the operational efficiency of the ship, while the Waste and Water Management KPI evaluates the capacity for sustainable waste management and water consumption on board. The use of targeted KPIs for each type of ship provides a more accurate picture of environmental performance and identifies the most effective strategies to reduce emissions and improve sustainability in the sector.

4.3. Transition KPIs relevant to banks in the maritime sector

In the context of the growing regulatory and financial pressure towards the decarbonisation of maritime transport, banks are progressively integrating a series of transition Key Performance Indicators (KPIs) into their credit assessment systems, aimed at measuring the degree of climate alignment of financed assets and monitoring their emission trajectory over time. These KPIs play a crucial role in the definition of selective capital allocation policies.

The KPIs relevant to banks can be divided into two main methodological categories[381]: quantitative, as they can be directly measured on a metric or accounting basis, and qualitative, relating to the organizational, strategic and information structure of the company. This distinction, adopted by bodies such as the Loan Market Association (LMA, 2023)[382], the TCFD[383] (2017) and the SBTi[384] (2022), allows for a holistic assessment of the risk profile and opportunities associated with the ecological transition of shipping companies.

Quantitative KPIs:

Quantitative KPIs represent the core of the technical-financial approach to assessing the climate performance of naval assets. They include:

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[381] Wijayanto, D. (2020). *The development of an operational KPI for energy efficiency ship operation*. World Maritime University.

[382] Loan Market Association (LMA). (2023). *Sustainability linked loan principles*.

[383] Task Force on Climate-related Financial Disclosures (TCFD). (2017). *Recommendations of the Task Force on Climate-related Financial Disclosures*.

[384] Science Based Targets initiative (SBTi). (2022). *SBTi Corporate Net-Zero Standard*.

Indicator	Description	Relevance for Banks	Regulatory Sources / References
CII (Carbon Intensity Indicator)	It measures the intensity of CO_2 emitted per ton of cargo transported per nautical mile.	Assessment of the energy efficiency of the ship; used to classify ships from A to E.	IMO MARPOL Annex VI, Regulation 26
EEOI (Energy Efficiency Operational Indicator)	It evaluates operational energy efficiency based on real consumption and load data transported.	Continuous monitoring of environmental performance; Useful for ship comparisons.	IMO Guidelines MEPC.1/Circ.684
Absolute CO_2 emissions (Scope 1)	Total amount of CO_2 emitted directly from the ship's operations.	Measurement of direct environmental impact; fundamental for ESG reporting.	GHG Protocol, TCFD Recommendations
Percentage of Alternative Fuels Used	Proportion of fuels with low environmental impact (e.g. LNG, methanol) used.	Indicator of the transition to more sustainable energy sources.	EU FuelEU Maritime Regulation
Share of Green Technology Investments (Green CAPEX)	Percentage of investments going to low-emission technologies.	Assessment of financial commitment to sustainability.	Sustainability-Linked Loan Principles
Technical Fleet Compliance (EEXI, SEEMP Part III)	Percentage of the fleet that complies with environmental technical standards.	Regulatory and operational risk indicator.	IMO MARPOL Annex VI, Rules 23 & 26

Table 7 *– Summary of quantitative indicators relevant for banks, including descriptions, banking relevance, and regulatory references.*

These indicators are integrated into ESG due diligence processes and are frequently associated with contractual conditions in green loans or sustainability-linked bonds, in which failure to achieve the objectives leads to economic penalties (rate step-ups) or loss of access to subsidized instruments.

Qualitative KPIs:

The qualitative KPIs complete the evaluation framework by offering strategic and organizational information on the actual ability of the shipping company to implement a credible, structured and transparent transition plan. Among the main ones:

Indicator	Description	Relevance for Banks	Regulatory Sources / References
Climate-Responsible Governance Structure	Presence of ESG committees, roles dedicated to sustainability in management.	Assessment of decision-making capacity and strategic commitment to sustainability.	TCFD Recommendations
Integration of Sustainability into the Corporate Strategy	Inclusion of climate targets in business and operational plans.	Indicator of the consistency between corporate strategy and sustainability objectives.	Science Based Targets initiative (SBTi)

Transparency and Quality of ESG Reporting	Adherence to recognized reporting standards (e.g. GRI, CDP).	Evaluation of the transparency and reliability of the information provided.	Global Reporting Initiative (GRI), CDP
Climate Scenario Analysis and Stress Test	Use of forecasting models to assess the impact of climate scenarios.	Measure of the company's resilience to future climate risks.	TCFD Recommendations
Participation in Voluntary Sector Initiatives	Participation in programs such as the Poseidon Principles[385] or Sea Cargo Charter.	Indicator of proactive commitment to sustainable practices.	Poseidon Principles, Sea Cargo Charter

Table 8 *– Summary of qualitative indicators relevant for banks, including descriptions, banking relevance, and regulatory references.*

These KPIs are analysed to attribute a climate alignment score or to segment risk according to degrees of exposure and resilience, as also recommended by the European Banking Authority (EBA) in its ESG risk reports[386].

In conclusion, the combination of quantitative and qualitative KPIs allows banks to assess not only the current emission profile of the company, but above all the strategic coherence, credibility and institutional solidity of its energy transition path. This approach, now incorporated into climate risk management processes, defines the basis for access to sustainable financial instruments, for classification as "green" assets according to the EU Taxonomy and for inclusion in the low-carbon portfolios of institutional investors.

4.3.1. Limitations and Challenges in the Integration of KPIs in Banking Financing Processes

Despite the growing focus on sustainability KPIs, their integration into banking financing processes presents significant challenges. One of the main obstacles is the lack of global standardization, which makes it difficult for financial institutions to compare ships' environmental performance and establish clear criteria for lending.

Currently, each shipping company uses different methodologies for data collection, resulting in discrepancies in results and difficulties in establishing reliable benchmarks. The BENCO study is also part of this debate, highlighting the need for greater integration between environmental KPIs and maritime financing strategies. If banks adopted the BIMCO KPI System as a benchmark for assessing ship sustainability, companies would be encouraged to improve their energy efficiency to obtain better access to credit.

[385] https://www.poseidonprinciples.org/finance/

[386] European Banking Authority. (2025, January 8). *Final report on guidelines on the management of environmental, social and governance (ESG) risks* (EBA/GL/2025/01).

Another problem is the quality and availability of data: many companies lack advanced tools to monitor emissions and consumption on a continuous basis, and transparency in reporting results is still limited. Banks, traditionally oriented towards financial and capital criteria in the assessment of investment risk, are gradually integrating environmental KPIs into their decision-making models, but this process requires time and regulatory adjustments. The paper "Maritime Sustainability and the Need for Global Performance Indicators in Shipping: An Empirical Investigation Based on the Shipping KPI Standard by BIMCO. World Maritime University." Di Darousos, E. F., Mejia Jr., M. Q., Panteladis, I., & Pastra, A. (2023)[387], highlights the need for integration of these KPIs in financial sector decision-making processes would be a key step to accelerate the energy transition. If financial institutions start basing their investment choices on measurable environmental parameters, the shipping sector could be encouraged to reduce its emissions and invest in more sustainable solutions. The adoption of principles such as the EU Taxonomy Regulations and funding related to sustainability are important steps forward, but the effectiveness of these tools will depend on the ability to define clear, verifiable and widely applicable KPIs.

Finally, Darousos et al. highlights the issue of profitability of investments in sustainable technologies: Many companies are reluctant to adopt new fuels or emission reduction systems because of the high initial costs and the difficulty in predicting long-term economic returns. Despite these challenges, the integration of sustainability KPIs in financing could be a strategic lever to accelerate the energy transition of the maritime sector and steer investments towards more sustainable solutions.

4.4. How banks read and evaluate: The weight of KPIs in the assessment of credit risk and in the allocation of credit in a climate-aligned logic.

The integration of ESG factors, and in particular climate transition KPIs, into the assessment of creditworthiness represents one of the most significant structural transformations in post-2020 bank finance. Following the guidance of the EBA (2025[388]) and the guidance of the European Central Bank (2024-2025[389]) on climate and environmental risks, credit institutions are required to review their risk measurement models to include, in a systemic way, also the impacts deriving from the energy transition[390].

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[387] Darousos, E. F., Mejia Jr., M. Q., Panteladis, I., & Pastra, A. (2023). *Maritime sustainability and the need for global performance indicators in shipping: An empirical investigation based on the Shipping KPI Standard by BIMCO*. World Maritime University.

[388] European Banking Authority. (2025, January 8). *Final report on guidelines on the management of environmental, social and governance (ESG) risks* (EBA/GL/2025/01).

[389] European Central Bank. (2024, January 30). *Climate and nature plan 2024–2025*.

[390] European Central Bank. (2020). *Guidance on climate and environmental change risks: supervisory expectations*.

In this scenario, key performance indicators, as described in the previous paragraphs**,** become a fundamental technical tool for measuring, estimating and pricing these risks from an ex-ante perspective. However, their use in banking practice has deeper methodological, regulatory and strategic implications.

Traditionally, credit risk assessment has been based on financial indicators (DSCR, EBITDA, leverage, equity), coupled with quantitative ratings and validated internal models. However, in the current context, this approach is insufficient to capture the new drivers of systemic risk**.** The climate transition introduces a new layer of risk – non-financial but potentially destabilizing – that is added to the traditional balance sheet parameters. Ships and fleets that are not aligned with international targets (Net-Zero 2050[391], IMO curves[392] or SBTi[393]) are now considered exposed to:

- Stranded asset risk related to the deterioration of the economic value of non-aligned assets causing it to be unable to operate economically due to new regulations,
- Reputational risk that limits access to increasingly sustainable logistics chains,
- Risk of technological obsolescence, caused by the regulatory and technological volatility introduced by European and international policy frameworks (e.g. maritime ETS, FuelEU Maritime, IMO GHG Strategy).

In this context, the shipowner's ability to demonstrate its transition path with solid KPIs becomes a direct component of the credit risk profile.

Banks, therefore, no longer read risk exclusively in ex-post terms, but through a predictive logic, in which KPIs are used to anticipate the probability of deterioration of creditworthiness as a function of regulatory, technological and market evolution[394]. In concrete terms, environmental risk is reflected in:

- Level of interest rate applied (differentiated pricing),
- Maximum credit limit available,
- Duration and structure of the loan (shorter maturities for less "transition-compatible" assets),
- Possible request for ESG or environmental representations, warranties, covenants, and events of default.

[391] International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector*. International Energy Agency

[392] International Maritime Organization. (2023). *IMO GHG strategy and emission reduction targets*.

[393] Science Based Targets initiative. (2022). *SBTi corporate net-zero standard*. Science Based Targets initiative.

[394] EBA – European Banking Authority. (2021). *EBA Report on Management and Supervision of ESG Risks for Credit Institutions and Investment Firms* (EBA/REP/2021/18)

A solid KPI system allows banks to segment customers according to the degree of climate risk and to allocate resources according to a selective and proactive logic.

The transition to a climate-adjusted logic, therefore, requires the use of environmental and operational KPIs as predictive proxies of the borrower's ability to maintain its bankability and credit quality in the medium to long term.

The integration of KPIs into risk classification systems is increasingly driven by European legislation on banking supervision, which obliges institutions to consider ESG factors within the ICAAP (Internal Capital Adequacy Assessment Process). According to the EBA[395] (2025) and ECB[396] (2024-2025) guidelines:

- Banks must map the ESG profile of borrowers and assess its impact on economic capital.
- They must incorporate environmental risks into internal rating models within time horizons consistent with the materialisation of transition risks.
- They are also required to assess capital adequacy with respect to shocks arising from climate scenarios.

In this perspective, the weight of KPIs is no longer an optional issue, but represents an element of prudential compliance and a prerequisite for credit continuity.

In the construction of internal rating models (IRBs), ESG KPIs can take on two fundamental functions[397]: The first way of integrating KPIs into bank rating systems concerns their use as Rating Modifiers: these are indicators that, by integrating with traditional quantitative parameters, determine a risk adjustment (e.g. penalization for ships with class E CIIs, premium per use >30% alternative fuel). The second function is that of dedicated ESG rating drivers, i.e. in some institutions (such as ING, Intesa Sanpaolo, Crédit Agricole), KPIs feed specific ESG modules that flow into the final credit score. These modules assess environmental aspects, disclosure, decarbonisation plans and climate governance and are updated at least annually[398].

The result is a multidimensional risk assessment, in which the shipowner who does not structure and demonstrate his transition trajectory with KPIs risks being classified as an *incremental risk that cannot be mitigated*, even in the presence of satisfactory economic performance.

Following the same logic, in addition to risk classification, transition KPIs are now used as an eligibility criterion and contractual condition for access to sustainable credit instruments:

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[395] European Banking Authority. (2025). *Final guidelines on the management of ESG risks (EBA/GL/2025/01)*.

[396] European Central Bank. (2024, January 30). *Climate and nature plan 2024–2025*.

[397] Task Force on Climate-related Financial Disclosures (TCFD). (2017). *Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures.*

[398] European Banking Authority. (2022). *ESG risk management and supervision*. European Banking Authority.

- In Sustainability-Linked Loans, KPIs define performance objectives (SPTs) whose achievement leads to a change in the interest rate (step-up/down). Example: CII reduction ≥15% within 3 years → spread reduction of 10 bps.
- In Green Loans, the allocation of funds is linked to projects that demonstrate baseline and impact environmental KPIs, verified by third parties (e.g. gCO_2/ton-mile reduction vs IMO benchmark).
- In ESG due diligence, the absence of measurable KPIs may lead to the exclusion of the shipowner from the eligible portfolio according to the SFDR Article 8 or 9 classification, or from guaranteed preferential finance programmes (e.g. InvestEU, European Investment Bank).

Banks thus apply a logic of selective credit allocation, rewarding operators capable of demonstrating alignment with credible Net-Zero trajectories, through transparent, traceable and monitorable KPIs over time.

For KPIs to be relevant within banking systems, they must meet the requirements of:

- Sectoral relevance: adaptability to specific ship categories (bulk, tanker, cruise, etc.).
- Methodological standardization: built according to recognized protocols (IMO, Poseidon Principles, ISO, GHG Protocol).
- Verifiability: based on digitally measured or tracked data (e.g. MRVs, sensors, IoT platforms) and subject to external assurance (ESG auditors or blockchain systems).
- Comparability with climate benchmarks: ability to be read in relation to emission reduction curves (e.g. IEA Net Zero 2050, SBTi maritime sector guidelines).

The absence of one or more of these requirements determines the inapplicability of KPIs in banking systems, which react by increasing collateral requests, applying penalizing rates or limiting the duration of the loan.

Ultimately, the ability to structure a transition plan based on solid KPIs has become a systemic competitive advantage[399]. Not only does it improve access to credit, but it enables:

- Inclusion in banks' climate-aligned portfolios (e.g. Poseidon-aligned fleets), borrowers with plans that are not credible or lack verifiable metrics are progressively excluded from green finance instruments or risk-controlled portfolios. On the contrary, those that demonstrate a well-documented, realistic and monitorable transition strategy can access improved conditions, both in terms of pricing and in terms of available capital.

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[399] Task Force on Climate-related Financial Disclosures (TCFD). (2017). *Final Report: Recommendations of the Task Force on Climate-related Financial Disclosures*.

- Maintaining the bank's ESG rating,
- Access to subsidised funds and public programmes to support decarbonisation,
- Priority in contracts with logistics operators and end customers sensitive to sustainability (e.g. companies that need to reduce their Scope 3).

The bank-centric logic is shifting from "can we finance this ship?" to "is this ship compatible with transition scenarios and our aggregate climate risk?". In this scenario, KPIs are the technical code through which this question is answered.

In the new paradigm of sustainable finance, KPIs are no longer simple reporting tools, but central components of the risk function and strategic levers of access to credit**.** Their presence, traceability and consistency with international standards today determine the bankability of a shipping company. In this context, the assessment of credit risk can no longer disregard the analysis of the debtor's climate trajectory, of which KPIs represent the objective, comparable, and priceable measure within banking models.

4.5. Summary tables: for each type of vessel, the most relevant KPIs and related benchmarks.

To provide an operational and comparable picture on the application of transition KPIs in the maritime sector, this paragraph introduces a series of summary tables that allow for a structured visualisation of the main indicators used in the process of assessing the sustainability of naval fleets. The tables are intended to integrate the analytical content of the previous paragraphs with application reading tools, useful for both operators in the sector and for lenders.

Three tables will be proposed:

1. A systematic classification of transition KPIs, divided into quantitative and qualitative categories, with their description and relevance for financial actors.
2. A selection of reference benchmarks associated with the main KPIs with the aim of providing validation and empirical feedback to the proposal developed, while making it possible to compare it with international objectives, science-based trajectories and regulatory thresholds, to increase the technical credibility and financial applicability of the identified parameters.
3. Finally, a mapping of the most relevant KPIs for each type of vessel.

The objective of these representations is twofold: on the one hand, to promote greater interpretative clarity on the parameters currently used to measure the environmental performance of maritime transport; on the other hand, to highlight the need for a differentiation of KPIs according to the operational and technological specificities of the different naval categories, to ensure a credible and technically sound assessment of the transition plans.

Ranking KPIs

The table below presents a detailed classification of the KPIs used to assess sustainability in the maritime sector. Each KPI is associated with a specific category – energy efficiency, environmental impact, economic performance, regulatory compliance and technological innovation – to offer a comprehensive view of ship performance.

	KPIs	Description	Units of Measurement
Energy Efficiency KPIs	**EEDI (Energy Efficiency Design Index)**	Energy efficiency of a new ship by design.	gCO_2/ton-mile
	EEXI (Energy Efficiency Existing Ship Index)	Energy efficiency of existing ships to verify their compliance with the new regulations.	gCO_2/ton-mile
	EEOI (Energy Efficiency Operational Indicator)	Energy efficiency of the ship under real operating conditions.	gCO_2/ton-mile
	CII (Carbon Intensity Indicator)	It measures the intensity of carbon emitted in relation to the transport carried out.	gCO_2/dwt-mile
	Fuel Consumption per Mile	Fuel consumption per mile sailed.	ton/mile
	Speed Optimization (Slow Steaming)	Speed reduction to improve fuel efficiency.	nodes
	Energy Consumption per Cargo Unit	Energy consumed for each unit of load transported.	kWh/TEU (per container) or kWh/t (per bulk carrier)
Environmental Impact KPIs	**Total CO_2 Emissions**	Total amount of CO_2 emitted by the ship.	ton CO_2/year
	SOx Emissions (Sulphur Oxides)	Sulphur emissions linked to the use of traditional fuels.	g/kWh
	NOx Emissions (Nitrogen Oxides)	Impact on air quality and climate change.	g/kWh
	Methane Slip	Release of unburned methane into exhaust gases (especially for LNG ships).	g/kWh

	Particulate Matter (PM2.5, PM10)	Emissions of particulate matter harmful to health and the environment.	g/kWh
	Scrubber Utilization Efficiency	Percentage of SOx reduction by scrubber.	%
	Ballast Water Treatment Efficiency	Ability of the ship to treat ballast water to reduce pollution.	%
Economic Performance KPIs	**OPEX (Operating Expenses per Day)**	Daily operating cost of the vessel.	$/day
	CAPEX (Capital Expenditure per Ship)	Cost of investing in new technologies.	$
	Fuel Cost per Mile	Fuel cost per mile sailed.	$/mile
	Payback Period for Alternative Fuels	Time needed to recoup the investment in alternative fuels.	years
	Carbon Credit Costs	Costs deriving from participation in carbon trading mechanisms.	$/ton CO_2
	ROI of Green Investments	Return on investments in sustainable technologies.	%
	Freight Rate Impact	Impact of the adoption of sustainable technologies on freight rates.	$/TEU or $/ton
Regulatory Compliance KPIs and Certifications	**Compliance with IMO 2023 Regulations**	Compliance with the new limits on CO_2 emissions.	Compliant / Non-compliant
	EU ETS (Emission Trading System) Compliance	Participation in EU carbon trading mechanisms.	€ spent per ton CO_2
	Number of Green Certifications	Number of environmental certifications obtained.	Number
	Adoption of Alternative Fuels	Percentage of the fleet using alternative fuels.	%
Technological KPIs for Energy Efficiency	**Battery Storage Capacity**	Capacity of batteries installed on hybrid/electric vessels.	MWh
	Shore Power Utilization	Percentage of shore power usage in ports.	%
	Wind-Assisted Propulsion Efficiency	Reduced fuel consumption through the use of rigid sails or rotors from Flettner.	%

	Air Lubrication System Efficiency	Reduction of hydrodynamic resistance thanks to air bubble systems.	%
	Hydrodynamic Hull Optimization	Improvements in the hull shape to reduce fuel consumption.	%

Table 9 *– Summary of KPI Analysis in the Shipping Industry*

This selection of KPIs was carried out through a detailed and granular analysis, based on authoritative and internationally recognized sources. These include directives from the International Maritime Organization (IMO) and reports and publications from DNV, a world leader in maritime consulting and certification, providing insights and guidance on best practices and emerging standards. In addition to these sources, academic studies and scientific publications analysing current and future trends in the maritime sector were examined. Organizations such as the International Chamber of Shipping (ICS) and the Baltic and International Maritime Council (BIMCO) regularly publish guidelines and reports that contribute to the definition and updating of relevant KPIs. Through the integration of these sources, it was possible to identify relevant KPIs that reflect the operational, environmental and safety needs of the maritime sector.

This classification was developed with the aim of associating specific financial instruments to the different types of ships, based on the reference KPIs. In this way, it is possible to identify the most appropriate financing solutions to support the energy transition in the shipping sector, ensuring that investments are targeted and effective.

The subdivision has been organized into five strategic macro-categories, each of which represents a key factor for the sustainability of maritime transport. Each KPI is accompanied by a description and the corresponding unit of measurement.

- Energy Efficiency KPIs: This section collects indicators that assess the fuel consumption and operational efficiency of ships. It includes regulatory indices such as EEDI (for new ships) and EEXI (for existing ships), as well as operational metrics such as CII (Carbon Intensity Indicator) and fuel consumption per mile. Some indicators, such as speed optimization (Slow Steaming), measure practical strategies for reducing consumption.
- Environmental Impact KPIs: Here polluting emissions and the efficiency of mitigation technologies are monitored. The table includes KPIs such as CO_2, SOx and NOx emissions, methane release (Methane Slip) and particulate matter (PM2.5, PM10). The effectiveness of technologies such as scrubbers (to reduce SOx) and ballast water treatment systems is also evaluated.

- Economic Performance KPIs: This section focuses on the financial sustainability of the ecological transition. It includes the daily operating cost (OPEX), the cost of fuel per mile sailed, and the payback period of the alternative fuel investment. Indicators such as the cost of carbon credits and the return on green investments (ROI) are also considered. The presence of these KPIs makes it possible to identify appropriate financial instruments, such as green bonds, subsidized loans for decarbonization and carbon pricing rates**.**
- Regulatory Compliance: KPIs and Certifications in this category, compliance with international regulations and the adoption of alternative fuels are monitored. Key indicators include compliance with IMO 2023 regulations, participation in the EU ETS and the number of environmental certifications obtained. These elements are essential to access public and private funds for the ecological transition, as well as tax incentives.
- Technological KPIs for Energy Efficiency: This section collects metrics related to the adoption of innovative technologies. The efficiency of solutions such as wind-assisted propulsion**,** hydrodynamic hull optimization and air lubrication systems is evaluated. Indicators related to the use of batteries and shore power in ports are also included. Investments in these technologies can be funded through venture capital, government grants, and innovation funding**.**

The table has been built to provide a clear and easily searchable structure, with the aim of:

- Distinguish between regulatory, operational and economic indicators, for a more balanced assessment.
- To allow the comparison between different ships and technological solutions, thanks to the use of standardized units of measurement.
- Support emission reduction and efficiency improvement strategies, providing concrete data for evidence-based decisions.
- Link KPIs to possible financial instruments so that each type of ship can be associated with financing solutions suitable for its ecological transition.

Benchmarks

KPIs	Units of Measurement	Benchmark Value or Optimal Range	Interpretive Scale	Source
EEDI	gCO_2/ton-mile	≤10	◍ ≤10 | ○ 10–15 | ● >15	IMO MEPC.308(73)
EEXI	gCO_2/ton-mile	≤ EEDI target	◍ compliant | ○ borderline | ● beyond	IMO MEPC.328(76)
CII (Carbon Intensity Indicator)	gCO_2/dwt-mile	A–B rating required by 2026	◍ A–B | ○ C | ● D–E	IMO CII Guidelines

				(MEPC.336(76))
EEOI	gCO_2/ton-mile	≤15	🟢 ≤15 | 🟡 15–20 | 🔴 >20	DNV Guidelines
Fuel Consumption per Mile	ton/mile	<0.15	🟢 <0.15 | 🟡 0.15–0.25 | 🔴 >0.25	Clarkson Research
Speed Optimization	knots	Slow steaming (10–15 knots)	🟢 <15 | 🟡 15–18 | 🔴 >18	Maersk Energy Efficiency Reports
Energy Consumption per Cargo Unit	kWh/TEU-mile	<50	🟢 <50 | 🟡 50–70 | 🔴 >70	IEA 2023
Energy Consumption per Passenger	kWh/passenger-mile	<2	🟢 <2 | 🟡 2–3 | 🔴 >3	Cruise Ship Efficiency Study
Total CO_2 Emissions	ton/year	<25,000 (for medium ship)	🟢 <25k | 🟡 25k–35k | 🔴 >35k	EU MRV Data
SOx Emissions	% m/m sulphurs	<0.5% global / <0.1% ECA	🟢 compliant | 🟡 near limit | 🔴 exceeds	MARPOL Annex VI
NOx Emissions	g/kWh	<2 (Tier III)	🟢 <2 | 🟡 2–3.4 | 🔴 >3.4	IMO Tier III Standards
Methane Slip	gCH_4/kWh	<1	🟢 <1 | 🟡 1–2 | 🔴 >2	IEA Maritime Fuel Outlook 2023 / DNV LNG Reports
Particulate Matter	g/kWh	<0.2	🟢 <0.2 | 🟡 0.2–0.4 | 🔴 >0.4	DNV Emissions Reports
Scrubber Utilization Efficiency	% removal	>90%	🟢 >90% | 🟡 80–90% | 🔴 <80%	EPA Guidelines
Ballast Water Treatment Efficiency	% invasive removal	>95%	🟢 >95% | 🟡 90–95% | 🔴 <90%	IMO BWM Convention
OPEX	\$/day	7k–10k (containership)	🟢 <10k | 🟡 10k–12k | 🔴 >12k	Clarkson Shipping Intelligence
CAPEX	\$/GT	300–700	🟢 <700 | 🟡 700–900 | 🔴 >900	DNV Ship Finance Outlook
Fuel Cost per Mile	\$/mile	<20	🟢 <20 | 🟡 20–30 | 🔴 >30	BIMCO Reports
Freight Rate Impact	% of revenue	<40%	🟢 <40% | 🟡 40–50% | 🔴 >50%	UNCTAD Transport Cost Review
Payback Period for Alternative Fuels	years	<5	🟢 <5 | 🟡 5–8 | 🔴 >8	IEA Maritime Study
ROI of Green Investments	%	>12%	🟢 >12% | 🟡 8–12% | 🔴 <8%	DNV Green Finance
Carbon Credit Costs	\$/ton CO_2	<100	🟢 <100 | 🟡 100–150 | 🔴 >150	EU ETS Market Data
Compliance with IMO 2023 Regulations	%	100%	🟢 100% | 🟡 partial | 🔴 none	IMO MARPOL Amendments
EU ETS Compliance	% coverage	100% on EU voyages	🟢 full | 🟡 partial | 🔴 none	EU ETS Directive 2023
Number of Green Certifications	count	≥2	🟢 ≥2 | 🟡 1 | 🔴 0	Green Award, ISO 14001

Adoption of Alternative Fuels	% fleet share	≥30%	◍ ≥30% | ◯ 10–30% | ● <10%	IEA 2024
Battery Storage Capacity	MWh	>5	◍ >5 | ◯ 2–5 | ● <2	DNV Battery Ship Report
Shore Power Utilization	% time at berth	>80%	◍ >80% | ◯ 50–80% | ● <50%	Port of LA Reports
Wind-Assisted Propulsion Efficiency	% fuel saving	>10%	◍ >10% | ◯ 5–10% | ● <5%	EU Interreg WASP
Air Lubrication System Efficiency	% drag reduction	>8%	◍ >8% | ◯ 5–8% | ● <5%	Silverstream Tech Reports
Hydrodynamic Hull Optimization	% efficiency gain	>10%	◍ >10% | ◯ 5–10% | ● <5%	DNV Hull Efficiency Study

***Table 10** - Summary of benchmarks*

Identification of KPIs by type of ship

Based on the previous table and, with the same logic, I have classified the different KPi (identified above) for each type of vessel studied in the initial phase of the methodology.

Ship Type	Efficiency KPIs	Environmental Impact KPIs	Economic Performance KPIs	Regulatory Compliance KPIs	Technological Efficiency KPIs
Containership	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Speed Optimization, Energy Consumption per Cargo Unit	Total CO_2 Emissions, SOx Emissions, NOx Emissions, Scrubber Utilization Efficiency, Ballast Water Treatment Efficiency	OPEX, Fuel Cost per Mile, Freight Rate Impact	Compliance with IMO 2023 Regulations, EU ETS Compliance, Number of Green Certifications	Battery Storage Capacity, Shore Power Utilization, Hydrodynamic Hull Optimization
Bulk Carrier	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Speed Optimization, Energy Consumption per Cargo Unit	Total CO_2 Emissions, SOx Emissions, NOx Emissions, Particulate Matter	OPEX, CAPEX, Fuel Cost per Mile, Payback Period for Alternative Fuels	Compliance with IMO 2023 Regulations, Adoption of Alternative Fuels	Wind-Assisted Propulsion Efficiency, Air Lubrication System Efficiency
Tanker Ship	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Speed Optimization	Total CO_2 Emissions, SOx Emissions, NOx Emissions, Ballast Water Treatment Efficiency	OPEX, Fuel Cost per Mile, Payback Period for Alternative Fuels, Carbon Credit Costs	Compliance with IMO 2023 Regulations, EU ETS Compliance	Air Lubrication System Efficiency, Hydrodynamic Hull Optimization
Fishing Vessels	Fuel Consumption per Mile, Speed Optimization	Total CO_2 Emissions, SOx Emissions, NOx Emissions	OPEX, Fuel Cost per Mile, Payback Period for Alternative Fuels	Compliance with IMO 2023 Regulations, Number of Green Certifications	Shore Power Utilization, Wind-Assisted Propulsion Efficiency

Ro-Ro Ship	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Speed Optimization	Total CO_2 Emissions, SOx Emissions, NOx Emissions	OPEX, CAPEX, Freight Rate Impact	Compliance with IMO 2023 Regulations, EU ETS Compliance	Wind-Assisted Propulsion Efficiency, Hydrodynamic Hull Optimization
General Cargo Ships	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Speed Optimization	Total CO_2 Emissions, SOx Emissions, NOx Emissions, Ballast Water Treatment Efficiency	OPEX, Fuel Cost per Mile, Freight Rate Impact	Compliance with IMO 2023 Regulations, Adoption of Alternative Fuels	Hydrodynamic Hull Optimization, Battery Storage Capacity
Passenger Ships	EEDI, EEXI, EEOI, Fuel Consumption per Mile, Energy Consumption per Passenger	Total CO_2 Emissions, SOx Emissions, NOx Emissions, Particulate Matter, Ballast Water Treatment Efficiency	OPEX, Fuel Cost per Mile, ROI of Green Investments	Compliance with IMO 2023 Regulations, Number of Green Certifications	Shore Power Utilization, Battery Storage Capacity, Wind-Assisted Propulsion Efficiency

Table 11 *– Overview of quantitative and qualitative KPIs categorized by ship type, covering efficiency, environmental impact, economic performance, regulatory compliance, and technological efficiency.*

This classification allows for an understanding of material KPIs that affect each individual type of ship for each area mentioned above, to build a coherent, comparable and technically sound assessment framework, which can be used by banking institutions to estimate the reliability, riskiness and potential climate alignment of the financed assets.

The tables are fundamental because they translate a complex and inhomogeneous system of indicators into a structured analytical tool, adaptable to each class of vessel, and capable of providing objective evidence on the ambition and technical feasibility of the transition plans. This addresses a central need of banks: to have verifiable technical parameters, anchored to recognised benchmarks (such as IMO, IEA or SBTi), to effectively integrate environmental and climate risks into due diligence and credit origination criteria.

In this way, the tables are not limited to cataloguing KPIs but take on the value of an operational decision-making grid, useful for strengthening the transparency of the dialogue between the shipping sector and the financial sector, and for promoting the selective allocation of capital towards the naval realities truly committed to decarbonization.

Chapter 5 – Integration of KPIs in Banking Processes and Operational Proposal for Financial Allocation in the Shipping Sector

5.1. Objective of the Chapter and Application Context

The aim of this chapter is to translate, in application and banking terms, the analysis carried out in the previous chapters, focusing on the integration of environmental and qualitative KPIs specific to the shipping sector within the risk management processes and allocation of financial instruments by credit institutions. This is a fundamental step in answering the research question: "How can banks integrate ship-type-specific sustainability KPIs in assessing financial risk and allocating the most appropriate financing instruments to incentivize the maritime sector's transition to decarbonization?"
After exploring the main technological and regulatory levers that are transforming the maritime sector (Chapter 1), and after deepening the banks' approach to climate risk and sustainable finance instruments (Chapter 2), the analysis focused on the identification of ship types, their characteristics relevant to the transition (Chapter 3) and the identification of specific metrics and KPIs, quantitative and qualitative levels, to assess their alignment with climate objectives (Chapter 4).
In this final chapter, we intend to propose an operational framework that allows to link the data collected on the individual vessel and its operator to a structured assessment of transition risk, translating this assessment into financial decisions: from the updating of the risk inventory to the definition of the Risk Appetite Statement (RAS), from the integration into the Risk Assessment processes (RAP) up to the selection and modulation of climate-linked financial instruments, such as Sustainability-Linked Loans (SLL) and Transition-Linked Loans (TLL).
Particular attention will be paid to the role that these KPIs play in fulfilling the requirements of the Basel regulatory framework: Pillar 1, with implications on the allocation of regulatory capital; Pillar 2, with inclusion in ICAAP/ILAAP processes and internal risk management models; and Pillar 3, which requires transparent ESG disclosure and increasingly granular reporting on climate risks and transition strategies.
The chapter therefore represents the phase of synthesis and application of the thesis: an attempt to structure, with a technical and banking slant, a model that allows informed financial choices to be made, consistent with environmental targets and able to concretely support the decarbonization of maritime transport. The proposed approach aims to bridge the gap between the technical valuation of the naval asset and the logic of capital allocation, laying the foundations for a truly climate-aligned and sector-aware finance.

5.2 From the Ship to Financial Instrument: Prioritization Based on Loan Size, Maturity, and Pricing

Based on the technical analysis of different ship types and the environmental KPIs identified in the previous chapters, this section proposes an advanced approach to allocating financial instruments. This approach goes beyond the static logic of a one-to-one risk–instrument association by adopting a dynamic and customized perspective that integrates three key parameters—loan size, maturity, and pricing—to develop tailor-made financial solutions for each ship segment, optimizing both environmental impact and financial sustainability.

The loan size is determined by the combination of capital expenditures (CAPEX) required for decarbonization interventions—such as engine retrofits, emission treatment systems, or alternative fuel conversions—and the residual market value of the vessel. Ships characterized by medium-high or high climate risk, such as Tanker Ships and Fishing Vessels, typically require substantial interventions, with CAPEX often exceeding 15–25% of the ship's market value. In these cases, it is necessary to structure large-scale loans, possibly through syndicated or blended finance, to distribute the risk among multiple financial institutions[400]. Conversely, ships with medium-low risk, such as Container Ships and Passenger Ships, are often already partially aligned with environmental standards and therefore require incremental investments with CAPEX below 10% of the ship's market value. For these vessels, standardized financial instruments like green loans or sustainability-linked loans are more appropriate, with smaller amounts and more straightforward transactions[401].

Maturity is another crucial aspect, closely tied to the expected payback period of the investment and the vessel's residual operational life. Ships with medium-high or high risk, requiring structural interventions such as propulsion system replacement or advanced emission reduction technologies, often need medium-to-long-term financing—typically 7 to 12 years—to align the project's cash flows with debt servicing and ensure financial sustainability[402]. For medium-low risk ships, where interventions are lighter and faster to implement, shorter maturities—typically 3 to 5 years—may be sufficient, with bullet or amortizing loan structures that maintain refinancing flexibility in response to regulatory updates (e.g. annual CII) or market developments[403].

Pricing represents a strategic element, as it must reflect both the estimated climate transition risk from the matrix and the expected environmental impact of the intervention. Ships with higher risk may

[400] Jameson, P., Sanders, U., Egloff, C., Krogsgaard, M., Dewar, A., Schack, L., & Larsen, D. C. (2024). *The Real Cost of Decarbonizing in the Shipping Industry*. Boston Consulting Group.
[401] DNV. (2023). *Poseidon Principles – Green finance in maritime*.
[402] BIS. (2022). *The pricing of carbon risk in syndicated loans*. Bank for International Settlements.
[403] MARAD. (2024). *Financing and Debt Overview*. Maritime Administration.

initially face higher interest rates or additional spreads (risk premium) to compensate for the uncertainty linked to the transition. These loans may include step-down or step-up clauses tied to ESG performance improvements, thereby incentivizing shipowners to accelerate decarbonization and benefit from more favorable economic conditions[404]. On the other hand, ships with medium-low risk profiles that are already aligned with most environmental standards can access more competitive pricing, potentially with interest rate discounts tied to achieving sustainability targets[405]. It is also important to consider the shipowner's specific creditworthiness, evaluated through financial indicators such as Net Debt/EBITDA or Interest Cover Ratio, and supported by technical covenants linked to environmental KPIs (e.g. EEDI, retrofit progress). Additionally, the choice of financial instrument influences pricing: green loans or green bonds may offer lower rates and linked pricing structures, while transition loans or transition-linked bonds may include dynamic spreads to manage transition risk uncertainty. In more complex operations, blended finance allows pricing differentiation through tranche structuring (senior, mezzanine, junior) depending on the risk perceived by investors[406].

In conclusion, adopting an approach based on loan size, maturity, and pricing allows banks to personalize their financial offering for each shipowner, tailoring it to the specific decarbonization strategy and the vessel's technical characteristics. This client-centric approach enables banks to prioritize their services according to the profile and needs of each client, building long-term, solid relationships with maritime operators while ensuring alignment with climate transition goals. This operational flexibility strengthens the role of financial institutions as strategic partners—not only in providing capital but also in guiding the sector's transformation towards sustainability and market competitiveness.

Type of Ship	Key KPIs	Estimated Risk	Loan Size	Maturity	Pricing
Container Ships	CII, EEDI, % alternative fuel, digitalization	Medium-low	Moderate (<10% of vessel value, standard green loans)	3-5 years (incremental upgrades, quick implementation)	Competitive pricing with potential rate reductions tied to sustainability KPIs
Bulk Carriers	EEOI, retrofit potential, % alternative fuel	Medium-high	High (15-20% of vessel value, possible transition/blended finance)	7-10 years (aligned with decarbonization investment)	Higher initial spreads, step-down mechanism based on ESG performance

[404] Alves, P., Gonçalo, J., & Pinto, J. (2023). *The pricing of sustainable syndicated loans*. EFMA.
[405] DNV. (2023). *Poseidon Principles – Green finance in maritime*.
[406] Simcox, C. (2024). *Financing the Green Transition: Innovative Models for Maritime Decarbonization*.

Tanker Ships	Absolute issuance, EEOI, ESG governance	High	High (15-25% of vessel value, possible syndicated/blended finance)	7-12 years (CAPEX payback and vessel life)	Higher spreads initially, step-down clauses tied to ESG milestones
Fishing Vessels	Engine efficiency, specific emissions	High	High (15-20% of vessel value, blended finance)	7-10 years (transition CAPEX)	Higher spreads initially, step-down pricing based on environmental compliance
Ro-Ro Passenger Ships	CII, Fuel Consumption, EEDI	Medium	Moderate (10-15% of vessel value, transition or green loan)	5-7 years (hybrid improvements)	Mixed pricing: dynamic spread based on ESG improvements
General Cargo Ships	EEDI, retrofit, governance	Medium-high	High (15-20% of vessel value, blended or transition loan)	7-10 years (aligned with retrofit)	Transition pricing: higher initial spreads with ESG-linked step-down provisions
Passenger Ships	CII, digitalization, % alternative fuels	Medium-low	Moderate (<10% of vessel value, sustainability-linked loans)	3-5 years (incremental upgrades)	Competitive pricing with potential interest rate reductions tied to sustainability goals

***Table 12** – Overview of ship types, key KPIs, estimated risk, and recommended financial structuring parameters*

5.3 Integration of KPIs into Banking Processes

The integration of specific KPIs for the shipping sector within banking processes is a key step in making the focus on sustainability and climate risk concrete in financial transactions. While responding to disciplinary logics (e.g. Pillar 2, ICAAP) and regulatory obligations (e.g. Pillar 3, TCFD), this integration requires a structured approach that involves the entire risk management cycle: from inventory to Compliance Disclosure Requirements.

First, it is critical that the banking Risk Inventory is updated to include sectoral climate risks related to shipping, such as CO_2 emissions per tonne-mile or operational carbon intensity indicators. This operation allows the bank to systematically identify exposures and define materiality thresholds consistent with ESG strategy and prudential risk principles[407].

[407] European Central Bank. (2022, November). *Good practices for climate-related and environmental risk management: Observations from the 2022 thematic review*. European Central Bank – Banking Supervision

Subsequently, the KPIs identified in this way are used to assess exposure to specific customer clusters (e.g. green vs. traditional shipowners) and to set out operating thresholds within the Risk Appetite Statement (RAS). In this phase, measurable and specific climate limits are defined, reflecting the climate sensitivity of the financed activities. The Risk Assessment (RAP) process then incorporates these KPIs into ESG scoring or rating models, strengthening the ability to measure and compare the sustainable performance of shipping customers[408].

Overall, the approach is consistent with guidance from supervisors and market participants that banks should:

- Map sectoral climate risks in their inventory, including quantitative and qualitative indicators.
- Assess the materiality of exposures against pre-established thresholds.
- Readjust the Risk Appetite Statement, defining climate limits by sector.
- Integrate KPIs into credit models, using dedicated ESG scorecards and sector quantitative parameters for pricing or granting credit

This integrated view, through the use of sectoral specific forward-looking and backward-looking KPI's, not only allows for more robust and forward-looking risk management but is also critical to ensure compliance with emerging regulatory requirements (e.g. Pillar 3 disclosures, ICAAPs, ESG stress testing) and to support a green transition of the maritime sector[409].

5.3.1 Materiality: Exposure assessment by customer cluster

Before proceeding to the formal integration of climate risks within the Risk Inventory, it is essential to assess the degree of materiality that these risks assume for the bank across different customer clusters. The materiality assessment makes it possible to distinguish between potentially negligible risks and those that, due to their size or probability of occurrence, are significant for the financial and capital stability of the institution. In this sense, climate materiality is not an absolute concept, but related to the type of activity financed, the nature of the client company and the sector context of reference.

In the shipping sector, this approach translates into a segmentation of the loan portfolio by homogeneous clusters of customers: for example, shipowners who invest in technologies with low environmental impact (green fleet), traditional operators with high emission intensity, companies operating on routes subject to stringent environmental constraints, etc. Each cluster is evaluated based

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[408] KPMG. (2023). *The need to act: Climate and environmental indicators in banks' strategies*.

[409] European Central Bank. (2022, November). *Good practices for climate-related and environmental risk management: Observations from the 2022 thematic review*. European Central Bank – Banking Supervision

on specific climate and operational KPIs, such as CII, EEOI or EEXI, as well as based on alignment with industry regulations and decarbonization trajectories.
In line with the EBA report[410], climate materiality must be assessed considering:

- multi-year time horizons (short, medium and long term);
- direct and indirect financial impacts, such as changes in credit rating, increased cost of funding or increased capital absorption.
- interconnections between climate risks and traditional risks, such as reputational or legal risk.

This assessment allows the bank to:

- calibrate the risk tolerance thresholds for each cluster.
- allocate analytical and monitoring resources in a proportionate manner.
- adjust its Risk Appetite Statement (RAS) on an objective and differentiated basis.
- orient the commercial strategy towards customers with a more climate-resilient profile.

In essence, climate materiality – supported by measurable indicators – allows for proactive portfolio management and represents an essential junction in the transformation of credit granting criteria in a sustainable way.
In the context of shipping, climate materiality is particularly relevant for several reasons. First, it is a carbon-intensive industry exposed to increasingly strict decarbonization targets and regulatory constraints (IMO 2023, EU ETS, FuelEU Maritime). Second, the long economic life of vessels increases the risk of technological obsolescence and stranded assets. Third, the sector is highly sensitive to geopolitical disruptions, fuel volatility, and physical climate hazards (e.g., sea level rise, extreme weather events). Therefore, from a banking perspective, shipping represents a sector with high transition and physical risk exposure, making climate materiality not only relevant but strategically essential for prudent credit risk management and capital planning.

5.3.2 Risk Inventory: Update to include sectoral climate risk

The *Risk Inventory* forms the backbone of a bank's risk management system. It is a systematic mapping, constantly updated, of all types of risk – both financial and non-financial – to which the institution is potentially exposed. Its function is to ensure that no material risk is overlooked within

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[410] European Banking Authority. (2021). *Report on management and supervision of ESG risks for credit institutions and investment firms* (EBA/REP/2021/18).

the overall management strategy, including the internal capital valuation (ICAAP)[411] and liquidity valuation (ILAAP)[412] processes.

In the current context, marked by a growing regulatory and market interest in sustainability, it has become essential to integrate climate and environmental risks into the Risk Inventory. In particular, for emission-intensive sectors such as shipping, updating the inventory requires the inclusion of specific risks related to the energy transition (such as misalignment with net-zero targets, or the introduction of regulations such as IMO 2023, EU ETS, FuelEU Maritime), as well as physical risks associated with extreme weather events (e.g. hurricanes, sea level rise, operational interruptions).

In line with these needs, the 2025 EBA[413] report highlights the importance for banks to update their Risk Inventory in a proportionate and systematic manner, considering climate risks, and clearly distinguishing between physical and transition risks. The Authority also recommends the use of precise, sectoral indicators, including climate KPIs relevant to shipping such as the *Carbon Intensity Indicator (CII),* the *Energy Efficiency Operational Indicator (EEOI),* the *Data Collection System (DCS)* and the *Energy Efficiency Existing Ship Index (EEXI)*. High values or values that do not comply with regulatory trajectories may indicate an increasing exposure to transition risk, both for individual counterparties and for entire portions of the loan portfolio. The approach promoted by the EBA provides that climate risks are treated as a traditional financial risk driver, and that their identification and assessment is carried out through both quantitative and qualitative metrics, with a forward-looking perspective consistent with climate objectives at European and national level.

In summary, updating the Risk Inventory by incorporating the climate KPIs specific to the maritime sector is essential to:

- avoid underestimation of vulnerable exposures to climate risk.
- strengthen prudent credit management;
- promoting the integration of climate factors into internal risk models.
- align with future supervisory requirements (e.g. EBA Guidelines, ECB Guide on Climate & Environmental Risk, CSRD).

A critical challenge in the concrete integration of climate risk into banking systems lies in the difficulty of linking sector-specific environmental data with traditional risk categories as defined by prudential standards. As observed in current banking practices and highlighted by both academic

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[411] European Central Bank. (2018, November). *ECB Guide to the internal capital adequacy assessment process (ICAAP).* European Central Bank – Banking Supervision.

[412] European Central Bank. (2018, November). *ECB Guide to the internal liquidity adequacy assessment process (ILAAP).* European Central Bank – Banking Supervision.

[413] European Banking Authority. (2025). *Final guidelines on the management of ESG risks (EBA/GL/2025/01*

and regulatory debate, there is a methodological gap between the measurement of climate performance (via KPIs) and the incorporation of transition risks into internal risk management processes, particularly under Pillar 2 frameworks. This gap manifests in two primary ways:

1. on the one hand, Pillar 1 supervisory models remain predominantly backward-looking, built on historical data and legacy indicators, which are insufficient to capture the forward-looking and dynamic nature of climate risks.
2. On the other hand, Pillar 2 processes, while more flexible and prospective in nature, are constrained by the lack of clear transmission channels that connect climate KPIs to traditional banking risks such as credit, operational, and market risk.

To address this challenge, a structured mapping exercise was conducted between key shipping climate KPIs and their corresponding transition risks, establishing a direct analytical bridge between environmental performance metrics and financial risk exposure from a bank's perspective. The resulting table identifies and analyses 30 KPIs relevant to the maritime sector, grouped into five categories: energy efficiency indicators, environmental impact indicators, economic performance metrics, regulatory compliance and certification indicators, and technological efficiency KPIs.
For each KPI, a specific transition risk has been identified, related to scenarios of inaction or regulatory non-alignment (such as technological obsolescence, regulatory exposure, or competitive disadvantage). These risks have then been associated with concrete transmission channels through which they may materialize as financial exposures for the bank. These include deterioration of client cash flow, asset devaluation and stranded assets, increased compliance costs, or heightened reputational risk. Finally, each KPI has been linked to a corresponding type of banking risk, based on the expected impact pathway—classified as credit risk, operational risk, or market risk, in accordance with the European prudential taxonomy.

	KPIs	**Transition Risk**	**Transmission Channel**	**Type of Bank Risk**
Energy Efficiency KPIs	EEDI (Energy Efficiency Design Index)	Technological obsolescence, non-compliance with IMO regulations	Write-down of naval assets, increased risk of default	Credit Risk
	EEXI (Energy Efficiency Existing Ship Index)	Technological obsolescence, non-compliance with IMO regulations	Write-down of naval assets, increased risk of default	Credit Risk
	EEOI (Energy Efficiency Operational Indicator)	High energy consumption, vulnerability to carbon costs	Reduced operating margins, lower cash flow	Credit Risk
	CII (Carbon Intensity Indicator)	Low carbon intensity rating	Regulatory and reputational limitations	Operational Risk
	Fuel Consumption per Mile	High energy consumption,	Reduced operating margins, lower cash flow	Credit Risk

		vulnerability to carbon costs		
	Speed Optimization (Slow Steaming)	Ineffective speed management for energy efficiency	Excessive consumption, operational inefficiency	Credit Risk
	Energy Consumption per Cargo Unit	High energy consumption, vulnerability to carbon costs	Reduced operating margins, lower cash flow	Credit Risk
Environmental Impact KPIs	Total CO_2 Emissions	Exceeding regulatory limits on emissions	Penalties, increased insurance and reputational costs	Operational Risk
	SOx Emissions (Sulphur Oxides)	Exceeding regulatory limits on emissions	Penalties, increased insurance and reputational costs	Operational Risk
	NOx Emissions (Nitrogen Oxides)	Exceeding regulatory limits on emissions	Penalties, increased insurance and reputational costs	Operational Risk
	Methane Slip	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Particulate Matter (PM2.5, PM10)	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Scrubber Utilization Efficiency	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Ballast Water Treatment Efficiency	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
Economic Performance KPIs	OPEX (Operating Expenses per Day)	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	CAPEX (Capital Expenditure per Ship)	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Fuel Cost per Mile	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Payback Period for Alternative Fuels	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Carbon Credit Costs	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	ROI of Green Investments	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Freight Rate Impact	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
Regulatory Compliance KPIs and Certifications	Compliance with IMO 2023 Regulations	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk

	EU ETS (Emission Trading System) Compliance	Exceeding regulatory limits on emissions	Penalties, increased insurance and reputational costs	Operational Risk
	Number of Green Certifications	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Adoption of Alternative Fuels	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
Technological KPIs for Energy Efficiency	Battery Storage Capacity	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Shore Power Utilization	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Wind-Assisted Propulsion Efficiency	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Air Lubrication System Efficiency	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk
	Hydrodynamic Hull Optimization	Possible non-alignment with decarbonization targets	Operating costs and reduced competitiveness	Credit Risk

Table 14 *– Mapping of sector-specific KPIs to their associated transition risks, transmission channels, and corresponding types of bank risk.*

This analytical framework enables a structured integration of shipping KPIs into the Risk Inventory, aligned with the latest EBA (2025) guidelines. It provides banks with a pragmatic tool to assess sector-specific exposures in a climate-aligned manner, supporting forward-looking risk management and the effective implementation of Pillar 2 supervisory expectations.

Moreover, the framework contributes to overcoming the current disconnection between forward-looking climate assessment and internal decision-making tools. It anticipates future disclosure requirements, climate stress-testing obligations, and alignment with proportionality principles, thus promoting a more coherent, sectoral, and risk-based approach to the integration of climate risk into banking practices.

5.3.3 Risk Appetite Statement (RAS): specific ESG limits

The *Risk Appetite Statement* (RAS) is one of the central tools of banking risk governance, as it allows the bank's strategy to be translated into concrete operational limits, defined in both qualitative and quantitative terms. Historically oriented towards the management of traditional financial risks (credit, market, liquidity), the RAS is now the subject of an evolution process aimed at structurally including climate risks.

In the case of the maritime sector, which is highly exposed to transition risk, the integration of specific climate limits within the RAS is now considered a prudent and proactive management practice. This translates, for example, into the definition of minimum environmental performance thresholds for the granting of credit (e.g. acceptable levels of *Carbon Intensity Indicator – CII*, or *Energy Efficiency Operational Indicator – EEOI),* in the limitation of exposure to customers with fleets not aligned with the IMO regulation or the net-zero pathway, or even in the introduction of exclusion criteria for highly emitting activities (e.g. use of fuels high sulfur content).

In the EBA 2021 Report, the Authority had already recommended the inclusion in the RAS of clear ESG objectives and limits, linked to the bank's strategy and consistent with its time horizons[414]. However, this orientation has found a much more concrete formalization in the recent Final Guidelines published on January 9, 2025[415], which provide for the obligation for European banks to:

- include in its RAS environmental, social and governance risks considered *material*;
- define climate limits based on measurable, updatable KPIs consistent with regulatory and sectoral evolution.
- assess climate risk according to forward-looking scenarios integrated into the ICAAP/ILAAP framework.
- make its strategies public through the climate disclosures provided for in the updated Pillar 3.

In addition, with the introduction of the EBA's ESG Dashboard[416] (April 2025), banks now have access to standardised climate indicators, which can be directly integrated into their RAS to strengthen dynamic exposure monitoring. The EBA encourages the use of these tools to ensure consistency between sustainability strategy, risk measurement and capital absorbed.

Finally, the ongoing regulatory evolution, including the publication of the EBA Guidelines on Transition Plans[417] (April 2025), further strengthens the role of the RAS as a mechanism for aligning risk management, long-term climate objectives and emerging supervisory requirements (CRD VI, CSRD, ECB Climate Expectations).

In summary, a *Risk Appetite Statement* that integrates specific and sector-specific climate limits – for emission-intensive sectors such as shipping – is no longer just a strategic option, but an essential regulatory safeguard to ensure the resilience of banking activity in the context of the ecological transition. ESG governance in banks today plays a strategic role in ensuring the alignment of

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[414] European Banking Authority. (2021). *Report on management and supervision of ESG risks for credit institutions and investment firms* (EBA/REP/2021/18).

[415] European Banking Authority. (2025, January 9). *Final guidelines on the management of ESG risks*.

[416] European Banking Authority. (2025, April 25). *ESG risk dashboard – April 2025 edition*.

[417] European Banking Authority. (2025, April). *Guidelines on transition plans under CRD VI.*

financing activities with international climate objectives. BNP Paribas[418], for instance, has integrated sustainability into its "GTS 2025" industrial plan, establishing ten official ESG performance indicators, including a dedicated ceiling for the decarbonization of the shipping sector. This ceiling is an integral part of the Group's CSR dashboard, whose implementation is monitored annually by the Executive Committee and the Board of Directors. This multi-level governance highlights how ESG objectives have become an integral part of the Group's strategic decision-making process, contributing to the alignment of financing with the green transition.

5.3.4 RAP (Risk Assessment Process): use of KPIs in ESG scoring or rating models.

In the context of integrated bank risk management, the *Risk Assessment Process* (RAP) plays a strategic role, as it allows the riskiness of counterparties to be systematically assessed, including not only traditional financial profiles, but also environmental, social and governance (ESG) profiles. The integration of climate Key Performance Indicators (KPIs) within the RAP is now an essential practice, especially for emission-intensive sectors such as shipping, where the ability to measure the climate impact of financed activities directly affects creditworthiness. The first guidelines in this regard have been provided by the European Banking Authority in its *Report on Management and Supervision of ESG Risks*[419], which outlines three methodological approaches: the *exposure-based* approach, the *portfolio alignment* method and the risk *framework method*), all of which share the need to adopt forward-looking tools, such as climate stress tests and scenario analysis. With the entry into force of *the EBA's* Final Guidelines on the Management of ESG Risks [420] (January 2025), the integration of climate KPIs into risk assessment processes becomes mandatory for all European banks. The guidelines establish that exposures must be assessed not only based on traditional financial risks, but also based on their vulnerability to transition risk (such as misalignment with IMO regulations or net-zero trajectories) and physical risk (e.g. exposure to routes subject to extreme weather events), using standardized metrics that are comparable over time. In parallel, the Net-Zero Banking Alliance (NZBA), in its 2023 technical guidance, promotes the use of sectoralized ESG scoring models, supported by quantitative indicators aligned with the goals of the Paris Agreement and scientific decarbonization targets, encouraging member banks to adopt specific KPIs for carbon-intensive sectors such as maritime[421].

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[418] BNP Paribas. (2023). *Universal Registration Document 2023*
[419] European Banking Authority. (2021). *Report on management and supervision of ESG risks for credit institutions and investment firms* (EBA/REP/2021/18).
[420] European Banking Authority. (2025, January 9). *Final guidelines on the management of ESG risks*.
[421] Net-Zero Banking Alliance. (2023). *Transition finance guide: Climate target setting and risk integration for high-impact sectors*.

The use of climate KPIs in RAP is realized through the construction of scorecards that can identify transmission channels that correct the company's transition risk to the bank's credit and market risks, through the use of KPi such as those collected and analyzed in the research, such as the *Carbon Intensity Indicator (CII),* the *Energy Efficiency Operational Indicator (EEOI)* and the *Energy Efficiency Existing Ship Index (EEXI)*. This data is translated into quantitative ESG scores, which contribute to the determination of probability of default (PD), loss in the event of default (LGD) and exposure at the time of default (EAD), thus influencing the credit quality assigned to the counterparty. The guiding principle is that of consistency between environmental sustainability and financial resilience, where a low emission profile becomes a proxy indicator of solidity in the long term. The 2025 EBA Guidelines[422] further strengthen this guidance, introducing a requirement to use forward-looking climate scenarios in the calculation of ESG scores, so that models take into account expected regulatory and operational transformations. The analyses must include the impact of carbon pricing instruments, the effect of regulations such as FuelEU Maritime or ETS Maritime, and the risks related to the obsolescence of non-compliant assets. ESG scorecards thus become predictive tools, capable of estimating how environmental KPIs will evolve over time, and what repercussions they could have on the counterparty's risk profile in the medium to long term.

However, integrating ESG KPIs into scoring models is not without operational challenges. One of the main ones concerns the availability and quality of data: ships not subject to IMO reporting obligations, SMEs or private operators often do not provide complete or verifiable indicators. Added to this is the difficulty of harmonizing ESG data from different sources, sometimes heterogeneous in methodology. To overcome these challenges, the most advanced banks are implementing statistical proxies, industry benchmarks, and ESG due diligence practices to close information gaps. In addition, tools such as the ESG Dashboard released by the EBA in April 2025[423], which aggregates and compares environmental indicators from European banks' Pillar 3 disclosures, offer valuable support to standardise assessments and strengthen the internal comparability of models.

In this framework, the integration of climate KPIs into the RAP offers several strategic and compliance benefits. In addition to improving accuracy in risk assessment and guiding pricing and credit allocation choices, it allows for anticipating impacts on capital requirements, meeting growing regulatory transparency needs (Pillar 3, CSRD) and demonstrating consistency between internal risk models and the institution's overall climate strategy. Ultimately, the RAP becomes not only a risk

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[422] European Banking Authority. (2025, January 9). *Final guidelines on the management of ESG risks*.
[423] European Banking Authority. (2025, April 25). *ESG risk dashboard – April 2025 edition*.

management tool, but a fundamental vehicle to guide the ecological transition of the financial sector, favoring the allocation of capital towards maritime activities compatible with a net-zero trajectory.

5.3.5 The integration of KPIs into the Basel Prudential Requirements: Pillar 1, 2 and 3

The integration of climate Key Performance Indicators (KPIs) into the Basel prudential framework is crucial to closing the current gap between climate risk exposure and banking risk management. In a sector like shipping—characterized by high emissions, technological inertia, and increasing regulatory scrutiny—this integration becomes even more pressing.

Within Pillar 1, although current regulations do not explicitly incorporate climate risk in the calculation of capital requirements, institutions are encouraged to recognize climate-related factors as amplifiers of traditional credit risk. Counterparties operating inefficient vessels or failing to meet IMO standards (e.g., CII, EEXI) may experience asset depreciation or reduced market access, with direct consequences for collateral valuation and exposure at default (EAD). The EBA 2025 Guidelines[424] foresee the progressive incorporation of climate risks into internal models and rating systems, anticipating a scenario in which ESG vulnerability may increase capital absorption.

However, as highlighted by Auzepy and Bannier (2025)[425], there is a marked dichotomy between the standardized and internal model-based (IRB) approaches. In the former case, the influence of climate risk depends on the integration made by external rating agencies, making it difficult for banks to have direct control. In the case of IRB models, integration into PD estimation models is hampered by the lack of historical data and the prevalence of short time horizons. Solutions such as conservativeness margins or override systems are still limited and subject to strong subjectivity.

Pillar 2, by contrast, offers an immediate space for operational integration. Through the ICAAP[426] and ILAAP[427] processes, banks must evaluate the resilience of their portfolios under climate-related stress scenarios and future transition pathways. The mapping of shipping-specific KPIs to transition risks, transmission channels, and impacted risk types (credit, operational, market) provides a structured approach to quantify climate exposures in risk inventories. This framework supports climate stress testing, portfolio segmentation by vulnerability cluster, and resource allocation consistent with climate resilience goals. Auzepy and Bannier's article highlights how banks have structured risk inventories that include physical and transition drivers, materiality assessments based

[424] European Banking Authority. (2025, January 9). *Final guidelines on the management of ESG risks*.
[425] Auzepy, A., & Bannier, C. E. (2025). *Integrating climate risks in bank risk management and capital requirements*. Springer Gabler.
[426] European Central Bank. (2018, November). *Guide to the internal capital adequacy assessment process (ICAAP)*.
[427] European Central Bank. (2018, November). *Guide to the internal liquidity adequacy assessment process (ILAAP)*.

on exploratory scenarios, sector maps and qualitative analysis. Once considered material, these risks are integrated into economic capital analyses and allocation plans. The inclusion of climate objectives in Risk Appetite Frameworks and the use of internal ESG scorecards are further levers to strengthen the integration of climate risks into credit and strategic decisions.

Finally, under Pillar 3, the role of disclosure has expanded significantly. Banks are now required to publicly report climate KPIs, portfolio alignment metrics, and transition plan progress. In the shipping sector, this means disclosing counterparty alignment with decarbonization trajectories and regulatory thresholds and reporting disaggregated data on emissions performance. The KPIs developed in this thesis offer a coherent basis for meeting these obligations, aligning prudential transparency with the principles of the CSRD and the EBA ITS 2025[428]. However, the paper points out that the quality and consistency of Pillar 3 reports remain heterogeneous, with difficulties in comparability between institutions. In sum, the integration of climate risk into the European banking system is still under construction, with experimental approaches and lack of standardization limiting its effectiveness. Pillar 2 emerges as the most advanced area, while Pillar 1 remains anchored in quantitative logic ill-suited to the systemic nature of climate risk. Pillar 3 assumes a strategic role in strengthening market discipline and incentivizing more robust disclosure practices.

In summary, by linking sector-specific KPIs to transition risk mechanisms and their transmission to financial exposures, this work contributes to operationalizing climate risk integration across the Basel framework. It addresses a critical pain point for banks: the difficulty of translating climate metrics into quantifiable, risk-based decisions. The proposed mapping between KPIs, transition risks, and banking risk categories provides a concrete tool for improving capital allocation, regulatory compliance, and long-term portfolio resilience in emission-intensive sectors such as maritime transport.

5.4 Recommendations and Policy Implications

The analysis conducted in the previous paragraphs has shown how the integration of the specific environmental KPIs for the shipping sector within banking processes (risk inventory, materiality, RAS, RAP, ICAAP and Pillar 3 disclosure) represents not only a regulatory evolution but also a strategic opportunity for sustainable finance. However, to make this operating model systemic, it is

[428] European Parliament and Council of the European Union. (2022, December 14). *Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting*. Official Journal of the European Union, L 322, 15–43.

necessary to decisively address some critical issues and formulate precise recommendations, distinct for financial actors, companies and regulators.
Based on the analysis carried out, I have outlined some policy recommendations aimed at both financial institutions and companies in the maritime sector.

Recommendations for financial institutions

1. Development of sectoral climate models integrated into IRB and ICAP processes. The application of Internal Ratings-Based Approach (IRB) models in the shipping context requires a profound revision of the modelling logic, which can no longer be based on historical parameters alone. As illustrated by Auzepy and Bannier (2025), the integration of climate risk into IRB processes is limited by the scarcity of quantitative data on climate-driven events and the structurally forward-looking nature of the transition. Banks must adopt hybrid approaches that combine climate metrics (e.g., CII, EEDI, EEXI, Scope 1–3) with climate override ratings, conservation margins (MoCs), and stress-test models based on NGFS or IEA Net Zero 2050 scenarios.
In the ICAAP context, it is essential to conduct specific scenario analyses for the maritime sector, disaggregating exposures by ship type, fleet age, degree of retrofit, and regulatory compliance (IMO 2023, ETS, FuelEU Maritime). These simulations must feed into the determination of capital buffers (capital add-ons), the allocation of internal capital and the Risk Appetite Framework, with climatic KPIs structured for homogeneous clusters of customers.

2. Strengthening bank-business partnerships and co-creating transition plans.
The technical, capital-intensive and regulatory-complex nature of shipping makes a top-down approach to climate risk assessment ineffective. A structured engagement strategy between banks and shipowners is needed, aimed at co-designing credible and bankable transition plans. These must include net-zero roadmaps, technological milestones, green CapEx detail, incrementally achievable decarbonization estimates, and KPIs aligned with the Poseidon Principles. Only through this interaction will it be possible to generate reliable datasets, which can be integrated into ESG-scoring models and ICAAP assessments.

Recommendations for companies in the maritime sector

1. Strategic use of KPIs to optimize access to credit and pricing conditions.
The introduction of ESG KPIs as technical proxies for risk represents a turning point for access to credit. The main ESG-linked financial instruments, such as Sustainability-Linked Loans (SLL), require measurable climate targets (e.g. average fleet CII reduction, alternative fleet %, retrofits

carried out). Credible governance, complemented by third-party metrics, not only allows you to attract capital on favourable terms, but also differentiate creditworthiness based on the transition trajectory. The most advanced banks are already experimenting with differentiated pricing through proprietary ESG scorecards that incorporate climate KPIs into credit spread rating and modulation.

2. Strengthening disclosure according to CSRD, EFRAG and TPT standards
Regulatory developments (CSRD, ESRS) impose stringent ESG reporting obligations also for companies. Shipping companies must structure reporting systems that can verifiably document environmental performance and progress in decarbonization plans. Alignment with the frameworks of EFRAG (ESRS E1), ACT (ADEME Transition Alignment Methodology) and the UK Transition Plan Taskforce (TPT) allows it to position itself competitively with respect to bank disclosure requests (Pillar 3, Art. 449a CRR). The use of asset-level indicators, sectoral benchmarks and ex-ante/ex-post verifications strengthens the company's credibility in the financial dialogue.
Following the operational recommendations addressed to banks and companies, some significant implications also emerge at a systemic and regulatory level. For the integration of climate KPIs into financial processes to produce concrete and scalable effects, it is in fact necessary to adapt the regulatory framework, capable of ensuring methodological consistency, data comparability and effective incentives for transition-aligned finance.

Harmonization of sectoral ESG frameworks for the maritime sector
The current regulatory fragmentation between the different ESG standards applicable to the shipping sector – including the EU Taxonomy, the Poseidon Principles, the IMO regulations (EEDI, CII, EEXI), the EBA Guidelines and the EFRAG ESRS – generates methodological confusion and hinders the homogeneous integration of climate risks into banking processes. This heterogeneity is reflected in the difficulty for banks to define comparable ESG scorecards, calculate consistent capital requirements and create reliable environmental performance benchmarks. According to the EBA 2025 Final Guidelines, climate risks must be treated as structural drivers of financial risk, and therefore must be based on consistent, validated and replicable metrics. However, in the absence of a harmonised industry standard, the assessment of climate materiality remains subjective and vulnerable to arbitrary judgments. The paper by Auzepy & Bannier (2025) highlights a strong heterogeneity among banks in the adoption of ESG indicators and in the modeling of climate-related PD/LGD. It is therefore desirable to create a minimum set of core climate KPIs for the maritime sector – such as EEXI, CII, % alternative fuels, Scope 1–3, CapEx alignment – to be integrated both into internal banking models and into Pillar 3 disclosures and corporate transition plans. A first step

in this direction is represented by the EBA's ESG Dashboard (April 2025), but European regulatory intervention is needed to foster convergence between technical approaches and regulatory obligations. The aim is to reduce the risk of methodological greenwashing and strengthen cross-sector and intra-bank comparability.

Introduction of regulatory incentives for transition-aligned finance

The second necessary intervention concerns the recalibration of the prudential treatment of financial exposures aligned with the climate transition objectives. Currently, banks that finance low-emission projects or net-zero business strategies do not enjoy any structured regulatory advantage over those who continue to support carbon-intensive activities. This paradox holds back the allocation of credit towards clean technologies and validated transition plans.

Considering the EBA Discussion Paper (2023) and the 2025 Guidelines on Transition Plans, there is room to introduce incentive measures such as:

- Green Supporting Factors (GSFs): reduced risk weights for exposures with climate KPIs aligned with scientific standards (e.g. -25% RWAs for full electric or green-hydrogen ready fleets);
- Climate-adjusted Pillar 2 Guidance (P2G): more flexible capital buffers for ESG-compliant portfolios.
- Rewards in disclosure requirements: simplifications in ESG reporting for operators with high environmental ratings.

According to Auzepy & Bannier, some banks have already introduced internal capital add-ons related to the climate misalignment of counterparties or the absence of credible transition plans. However, without explicit regulatory recognition, these measures remain weak in terms of validation and inapplicable in standardised models.

In addition, tax incentives or privileged access to public funds (NextGenEU, InvestEU, Innovation Fund) for instruments such as SLL, TLL, or transition bonds, would represent a further stimulus to the spread of climate finance in the maritime sector. This approach has already been proposed by the Platform on Sustainable Finance in relation to "intermediate technologies" in hard-to-abate sectors.

In summary, without clear and proportionate incentives, green finance risks remaining limited only to operations with evident reputational returns, excluding precisely the maritime realities that would most need support to start a structured transition path.

Conclusions

The ecological transition of the maritime sector represents a systemic and strategic challenge, involving technological, regulatory, financial and operational aspects, with significant implications on a global scale. The work carried out in this thesis addressed this complexity by adopting a multidisciplinary perspective, proposing an operating model for the integration of environmental KPIs in banking risk assessment and credit allocation processes.

However, as highlighted by the first *Getting to Zero Coalition Action Framework*[429], the trajectory towards zero-emission shipping still appears fragile and fragmented. The analysis of 76 companies shows a strong asymmetry in the maturity levels of decarbonization initiatives, with many actions still in the planning or study phase. Green corridors, a symbol of the transition, remain in most cases prototypes on paper, hindered by the high costs of e-fuels and the absence of de-risking financial instruments that allow them to be scalable.

A particularly emblematic figure concerns the uneven nature of investments: while the construction of new ships and port infrastructures raises more than 70% of capital, retrofits, professional training and the involvement of the financial sector remain residual. In particular, the training of seafarers, essential for the safe use of alternative fuels such as methanol, ammonia and hydrogen, is still in an embryonic phase: more than 40% of the initiatives are in the design phase, highlighting a regulatory and operational gap in the education sector.

At the same time, despite some infrastructural progress, barriers related to spatial constraints, uneven urban planning and lack of institutional coordination remain. Even the production of alternative fuels, while showing positive signs with some industrial pilot projects, suffers from the lack of binding off-take contracts, preventing the consolidation of demand and creating a vicious circle between commercial uncertainty and underinvestment. Today, only 15% of ships actually operate with zero emissions, and the adoption of advanced technologies is proceeding cautiously, held back by the scarcity of green fuels and business models that are not yet consolidated.

In the face of these critical issues, the transition is still strongly conditioned by exogenous factors**:** the absence of synergy between supply and demand, the lack of risk mitigation tools, regulatory uncertainty and the fragmentation of governance. To overcome this experimental phase, it will be essential to activate targeted public policies, introduce innovative contractual instruments (such as

[429] Spiegelenberg, F., Fahnestock, J., & Chamilothoris, L. (2025). *Getting to Zero Coalition Action Framework: Documenting actions towards decarbonising shipping*. Global Maritime Forum

contracts for difference on maritime fuels), and build coordinated industrial and institutional partnerships, capable of supporting a systemic evolution of the sector.

In this perspective, finance can and must take on a transformative role. Banks are strategically positioned to lead the transition, not only through prudent risk management, but by directing capital towards projects that are truly aligned with global climate goals**.** The definition and adoption of robust environmental sector KPIs – such as CII, EEOI, EEXI and the percentage use of alternative fuels – allow financial institutions to integrate sustainability into the most consistent rating, pricing and selection logics: from green bonds to sustainability-linked loans, up to more flexible instruments such as transition-linked loans.

In this regard, a further conceptual and operational impetus comes from the report *"Nature Positive: Corporate Assessment Guide for Financial Institutions"* (World Economic Forum, 2025)[430] which underlines how financial institutions are strategically positioned to lead this new frontier of sustainability as well, supporting the transformation of value chains through assessment and financing tools based on environmental indicators related to nature. This report provides a further element of reflection that has recently emerged regarding the role of banks not only in the climate transition, but also in the nature-positive transition, oriented towards the protection of biodiversity and ecosystems. The document identifies 11 specific KPIs – from land and water use to impacts on biodiversity – and proposes an assessment model like the one already established for climate. This reinforces the idea that, to be truly effective in driving the ecological transition, banks must adopt an integrated and anticipatory approach, extending their risk management and credit allocation systems to non-climate environmental impacts as well**.** The validation of business plans through granular indicators – environmental, climatic and now also natural – is therefore a central element to ensure the credibility, bankability and transformability of the projects financed, strengthening the active role of financial institutions in building a sustainable economy on all environmental fronts.

In this scenario, innovative financial mechanisms play a central role. Instruments such as blended finance, green and blue bonds, pay-as-you-save models, sustainability-linked loans and public-private blending, offer concrete pathways to overcome the green premium and unlock investments in clean technologies and alternative fuels. But regulatory harmonization, which is still uneven today, is equally crucial: the inclusion of maritime transport in the EU ETS and the introduction of the FuelEU Maritime Regulation are important steps, but the absence of globally shared standards and the failure

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430 World Economic Forum, & Oliver Wyman. (2025). *Nature positive: Corporate assessment guide for financial institutions*. World Economic Forum

to include some technologies in the EU Taxonomy (such as dual-fuel ships) risk frustrating the sector's efforts.

A further element supporting the need for a granularly technical and financially structured approach is represented by the new tiered global fuel standard system adopted by the IMO as part of the MEPC 83 strategy[431]. This system provides, starting from 2028, progressive targets for reducing the carbon intensity of marine fuels, with thresholds increasing to 43% by 2035. Ships will be assessed based on their adherence to these limits (compliant, Tier 1, Tier 2), with the possibility of compensating for non-conformities through flexible mechanisms based on surplus credits or Remedial Units. This approach creates a truly regulated carbon market for shipping, where the use of zero- or near-zero-emission fuels will be rewarded, and environmental performance will become a tradable financial asset.

For banks, this implies the need to incorporate a vessel's ability to generate or purchase compliance units into credit models, which further reinforces the strategic value of sectoral environmental KPIs and their function as proxies for risk and return. Not integrating these variables into ESG models would be tantamount to neglecting a structural component of future competitiveness in the sector.

More effective multi-level governance is therefore needed, involving development banks, regulatory authorities, shipowners, ports, energy suppliers and training operators in an integrated public-private ecosystem. The co-design of green routes, the standardisation of sectoral ESG indicators and the creation of platforms like energy PPAs to aggregate demand for e-fuels should be promoted.

In conclusion, the decarbonization of shipping requires an integrated strategy, in which finance, policies and industry move in a synergistic way. Only through the activation of innovative financial instruments, stronger global governance, harmonized regulation and the widespread adoption of sectoral environmental KPIs will it be possible to transform the signals of current activism into a structured and scalable transition towards climate neutrality. Banks, if adequately equipped, will not only be able to lead this transformation, but consolidate their role as protagonists in sustainable, resilient and inclusive economic growth.

[431] International Maritime Organization. (2024). *MEPC 83: Tiered global fuel standard and compliance mechanism overview*. International Maritime Organization.

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