ZERO-EMISSION SHIPPING REPORT

Accelerating Maritime Decarbonization

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1. Executive Summary

This report presents results of our study that examines the adoption of zero-emission shipping (ZES) in the **Dutch Maritime Industry**, analyzing the complex interactions of technological, economic, organizational, and institutional factors that shape investment and operational decisions. Using a participatory **Group Model Building approach** hosted at **Koninklijke Vereniging van Nederlandse Reders (KVNR, The Royal Association of Netherlands Shipowners)**, we engaged maritime stakeholders including **Shipowners and Ship-operators, Shipbuilders and System Integrators, Fuel-cell and Battery Manufacturers, Energy Suppliers, Infrastructure Stakeholders, Financial Institutions** to identify and evaluate the key drivers and barriers influencing adoption. Over 250 factors were collected across five sessions, which were condensed into a focused set of 40+ critical factors. Stakeholders scored these factors before and after deliberation on their importance for adoption, revealing significant shifts in perceived importance and highlighting the value of structured dialogue in building a shared, system-wide understanding of the interdependencies that exist between the factors collected shaping the transition toward zero-emission shipping.

Causal loop diagrams developed from the sessions illustrate the interactions among the factors and the reinforcing and balancing feedback mechanisms that shape the transition to zero-emission systems. The analysis shows that adoption factors are highly interdependent, with progress in one area such as technology readiness, regulatory alignment, or infrastructure investment depending on complementary developments across the system. Key insights include the critical role of early investment in **port and energy infrastructure**, coherent **multi-level regulation**, credible **certification and safety standards**, and **cross-stakeholder collaboration**. These factors together reduce perceived risk, enable scalable technology deployment, and encourage private investment.

For managers, policy makers and decision-makers, the findings show that the transition to zero-emission shipping involves interconnected processes rather than isolated initiatives, requiring holistic system management that accounts for feedback effects, shared dependencies, and the timing of actions across stakeholders. Understanding a more comprehensive system view and the interdependencies between factors and stakeholders helps reveal potential leverage points, patterns of coordination, and areas influencing strategic decision-making related to adoption. The report presents insights from the sessions that describe these relationships across stakeholder groups in the transition toward a more sustainable maritime industry.

This project has been made possible through funding from the Netherlands Organization for Scientific Research (NWO) as part of the SEANERGETIC program. It is an ongoing project, and the activities and outcomes presented in this report form part of Work Package 4, which focuses on understanding the transition toward viable business models for zero-emission energy systems in the maritime industry.

2. Understanding the Challenge

The maritime sector, which underpins around 80 % of global trade by volume, is also responsible for an estimated 2.5–3 % of global greenhouse gas emissions, equivalent to over one billion tonnes of CO_2 annually (IMO, 2020). Without decisive action, these emissions could rise by 18 % by 2050 due to growing trade volumes (MM, 2023). Recognizing this challenge, the International Maritime Organization (IMO) adopted in 2023 a revised greenhouse-gas (GHG) strategy that sets the goal of achieving net-zero or near-zero GHG emissions from international shipping by or around 2050. The strategy includes indicative checkpoints to reduce total GHG emissions by at least 20 % (striving for 30 %) by 2030, by at least 70 % (striving for 80 %) by 2040, and to ensure that zero or near-zero GHG fuels represent at least 5 % (striving for 10 %) of total energy use by 2030 (IMO, 2023).

Building on these global commitments, the Maritime Masterplan of the Netherlands articulates a national ambition "to develop, build, and operate reliable, competitive, and modular climate-neutral ships" through a cyclical innovation chain (MM, 2023). The plan foresees the development of around 40 demonstration vessels powered by hydrogen, methanol, and LNG with carbon capture, expected to reduce 200 megatons of CO_2, 300 kilotons of NO_x, and 20 kilotons of particulate matter by 2050. Beyond its environmental ambition, it anticipates an economic impact of €4.1–4.6 billion and aims to double Dutch ship production from 80 to 140-170 vessels per year, highlighting how decarbonization is both a strategic and economic opportunity for the Dutch maritime ecosystem to strengthen Europe's open strategic autonomy and global competitiveness.

Despite the emergence of alternative-fuel vessels, data reveals that most new ship orders remain conventional-fueled (Andersen, 2025). For example, in a mid-2025 analysis Det Norske Veritas (DNV) shows that only around 17% of newbuild orders over the prior 12 months were for vessels capable of using alternative fuels, meaning that approximately 83% of that order-book tonnage remains conventional-fueled.

To elaborate further:

- In the first half of 2025, DNV reports that **151 alternative-fueled vessels** were ordered, representing **19.8 million gross tons (GT)**, a 78 % increase in GT compared to the same period in 2024.
- Yet in that same period the conventional-fueled share remains dominant. Among the alternative-fueled orders, the largest share (87 vessels, 14.2 million GT) were LNG-fueled, underlining that many orders still rely on transitional rather than zero-carbon fuels.
- While DNV noted promising momentum for methanol, ammonia and hydrogen, these remain niche in the order book, and the infrastructure, supply chains and regulatory clarity remain major inhibitors.

These figures underscore that although alternative fuels are gaining attention and orders are rising in absolute terms, the scale of conventional fuel newbuilds remains large. In the current context, there is still much risk and uncertainty, where decisions may for instance result in stranded assets and exposure to long retrofit downtime.

Against this backdrop, this study explores the research question: *What factors influence organization adoption of green technology in an industry, and how do these factors interact with one another?* The aim of the study is to develop a system-wide understanding of the technological, organizational, economic, and institutional factors shaping the adoption of zero-emission technologies in the maritime industry, and to identify how these factors interrelate to influence organization decision-making under uncertainty. By examining these interconnections, the study seeks to contribute to a deeper understanding of the dynamics that enable or hinder progress toward more sustainable and viable business models in the maritime industry. This research is part of the SEANERGETIC program and is funded by

3. The System Dynamics Approach

The System Dynamics approach helps build understanding of complex problems and interactions that has been used for sustainable transition studies (Gürsan & de Gooyert, 2021; Janipour, de Gooyert, Huijbregts, & de Coninck, 2022). We involved a wide variety of stakeholders with various interests within and related to the maritime industry and organized workshops according to the format put forth by the literature (Vennix, 1999). Group model building is specifically suited for workshops where diverse stakeholders collaborate to structure a problem (Rouwette, Korzilius, Vennix, & Jacobs, 2011), as it applies System Dynamics principles to capture feedback loops, interdependencies, and dynamic behaviors, using participatory modeling to translate complex system structures into shared understanding. The model building process consists of stakeholders taking part in the workshop in which they construct their perspectives of a part of reality on a certain issue (Franco & Montibeller, 2010), in our case the transition to zero-emission technologies in the Dutch Maritime industry. The model is built step by step to ensure that it accurately represents the viewpoints of the stakeholders participating, each time a causal relationship was established a question was asked whether all participants agreed on the relationship. Each workshop started the same way with all sessions building from the same seed model, where the main dependent factor was the '***Adoption of Zero-Emission Technology***,' and participants were given a factor collection form to provide the factors that would be mapped into the system view. We used a Causal Loop Diagram (CLD) to map out the relations among the factors (Vennix, 1996) during each workshop. Using Group Model Building techniques, participants mapped causal relationships among factors influencing adoption of zero-emission systems (ZES). The sessions generated causal loop diagrams that captured feedback mechanisms such as how regulatory clarity affects investment confidence and how infrastructure availability shapes fuel costs. This participatory process created both a research output and a shared industry learning exercise. Stakeholders could visualize how their individual actions link to industry-wide dynamics, encouraging a more collaborative mindset toward transition planning.

3.1. Who Participated

Participants represented key actors in the Dutch maritime ecosystem: shipowners and ship-operators, shipbuilders and system integrators, fuel-cell and battery manufacturers, energy suppliers, infrastructure stakeholders and financial institutions. Participants were identified through purposive sampling, guided by three key criteria and facilitated by the support of the **KVNR**. The selection criteria required that participants (1) possess a minimum of five years of professional experience in the maritime or closely related industries, (2) hold direct relevance to decision-making processes concerning zero-emission shipping, and (3) occupy positions of decision authority or exercise substantial influence within their organizations (Rajah & Kopainsky, 2025). Together, these criteria ensured that participants were highly knowledgeable and experienced regarding the adoption of zero-emission shipping.

Between October 2024 and June 2025, five participatory workshops were held, each lasting about three hours at KVNR's office in Rotterdam. Each workshop was designed to have diversity of stakeholders present representing diverse interests and viewpoints in the industry. There were 7 participants on average per workshop each from a different stakeholder type to ensure a diverse mix of participants from the maritime industry.

3.2. Understanding System Interactions through Causal Loop Diagrams

To understand how different factors influence each other, the models developed during the Group Model Building (GMB) sessions were translated into **Causal Loop Diagrams (CLDs)** using **Vensim PLE software**. These diagrams help visualize how changes in one part of the system affect others over time.

Each CLD is built around three main elements:

- **Factors** which represent key factors in the system (e.g., technology readiness, cost, regulation).
- **Causal links**, which show how one factor is linked to another (the arrow).
- **Polarities**, which describe whether the relationship moves in the same or opposite direction.

A **reinforcing loop** means that when one factor increases, the other also increases (and vice versa). A **balancing loop** means that when one increases, the other decreases. When factors are connected in a circular chain, they form a **feedback loop**, which can either reinforce or balance change within the system.

- A **Reinforcing Loop (RL)** strengthens or accelerates change over time. A reinforcing loop (RL) contains an **even number** of negative polarities (0, 2, 4, …) and amplifies change within the system. For example, increased adoption of zero-emission shipping can lower technology costs, which in turn encourages even greater or further increasing adoption.
- A **Balancing Loop (BL)** stabilizes the system. In contrast a balancing loop (BL), which contains an **odd number** of negative polarities (1, 3, 5, …), counteracts change and promotes system stability. When growth or change becomes too strong, feedback within the loop slows it down and restores balance.

In Figure 1, the **blue arrows** show positive relationships and **red arrows** show negative ones. Together, these loops help visualize how economic, regulatory, organizational, and technological factors interact dynamically. This approach makes it easier to identify where interventions or policies could have the greatest long-term impact on accelerating zero-emission shipping.

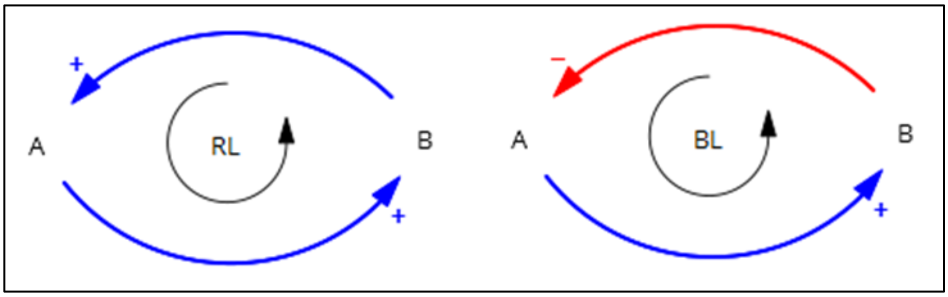

Figure 1: System dynamics notation. The arrows indicate that a causal relation exists between the factors. '+' indicates positive causal relation, '-' indicates a negative causal relation.

3.3. Four Main Factors Influencing Adoption

Based on the literature (Qin, Muskat, Ambrosini, Mair, & Chih, 2025; Koljonen & Chan, 2024; Sahoo, Kumar, & Upadhyay, 2023; Aragòn-Correa, Marcus, & Vogel, 2020), the adoption of zero-emission systems is shaped by four main factors: **Technological, Economic, Organizational, and Institutional**. These factors guided the analysis of the Group Model Building sessions, where participants identified more than 250 factors influencing adoption, with roughly 50 factors per session on average. Participants acted as "Knowledgeable Agents" (Vennix, 1996) to map the interactions between factors in Causal Loop Diagrams (CLDs), agreeing on whether each relationship was positive or negative. These interactions were considered in the context of the current maritime landscape, recognizing that factors can change over time due to shifts in regulations, technology, markets, or infrastructure.

The adoption of zero-emission systems is complex, with many interdependencies between factors. To manage this, the full set of factors was condensed into over 40 key factors forming the overall system. The large number and interconnectedness of factors highlight why decision-making is challenging, as small changes in one area can have ripple effects throughout the system. By mapping these factors and their interactions in CLDs, we can visualize the feedback loops and key relationships that drive or constrain adoption, providing stakeholders with a clear picture of the dynamics shaping the transition toward zero-emission shipping.

To create an overall view of the system, the five causal loop models from the separate workshops were combined into a single aggregated model. This was done by comparing the individual workshop models to identify areas of overlap, complementary elements, and any contradictions across the factors. The aggregation followed three criteria: convergence, where similar feedback structures appeared across models; complementarity, where different models highlighted related but distinct processes; and salience, where certain themes recurred across workshops or carried particular significance in explaining barriers and drivers (Newberry & Carhart, 2024; Rajah & Kopainsky, 2025). Using this state of the art approach embedded within the literature allowed the aggregated model to preserve the insights from each workshop while providing a comprehensive picture of the systemic interactions shaping adoption (Linneberg & Korsgaard, 2019; Gioia, Corley, & Hamilton, 2013; Rouwette, Korzilius, Vennix, & Jacobs, 2011). This method aligns with practices in participatory system dynamics, where multiple stakeholder-specific models are systematically compared and integrated to generate a clear representation of the system's key feedback loops (Rajah & Kopainsky, 2025).

4. Participant Before and After Scoring Factor Importance

Participants were asked to identify the factors they considered most influential for the adoption of zero-emission shipping (ZES) and to assess the relative importance of each factor. During the Group Model Building sessions, participants initially scored each factor on a scale of 1 to 10, with 10 representing the most important driver or barrier to adoption and 1 the least. Given the large number of factors collected (over 250), we focused the scoring analysis on the 30 most frequently mentioned factors, as assessing all factors in detail was not practical. After group discussion and collective deliberation, participants re-scored their original factors to capture any shift in perception. This process was important because it allowed stakeholders to reflect on the interdependence and system-wide implications of different factors, rather than assessing them in isolation. Comparing scores before and after the sessions revealed how structured dialogue reshapes understanding of the key drivers and constraints in the transition to zero-emission shipping.

The comparison of participants' scoring before and after the group model building sessions, as can be seen in Figure 2, reveals significant shifts in how stakeholders perceive the relative importance of different factors driving or constraining the zero-emission transition. Several factors saw a marked increase in their assessed importance following the deliberative process, indicating that through collective discussion and knowledge exchange, stakeholders recognized dimensions of the transition they had initially underestimated. For instance, **public perception and social pressure** (+81%) and **total cost of ownership** (+87%) experienced the strongest upward re-evaluation. Both factors were initially scored relatively low, suggesting that stakeholders underestimated their salience when considering the transition in isolation. However, as the discussion unfolded, it became clear that societal legitimacy, customer expectations, and the comprehensive cost profile of new technologies are crucial determinants for adoption. Similarly, **technology scalability** (+68%) and **fuel safety** (+60%) became much more prominent after the sessions, pointing to the realization that the success of pilot projects and technical innovations ultimately depends on their ability to scale safely across the fleet.

Regulatory issues also gained substantial traction after group reflection. **National regulations** (+48%), **multi-level regulatory alignment** (+49%), and **technology certification** (+55%) all emerged as more central to the transition than stakeholders initially assumed. This collective re-assessment indicates that the fragmented and multi-layered nature of maritime governance, alongside the need for credible certification pathways, constitutes a critical barrier to investment certainty and adoption. The group discussion appeared to foreground how misalignment between global, regional, and national regulations could delay scaling efforts and increase risk exposure to organizations. In contrast, some regulatory factors such as **regional regulations** (−22%) and **regulatory clarity** (−9%) declined in importance. This downward shift suggests that while regulation as a whole was reinforced, the emphasis moved away from individual jurisdictions or perceived transparency toward the broader challenge of coherence and alignment across multiple layers.

Other factors experienced notable decreases, reflecting a recalibration of pre-conceived notions participants brought into the sessions. For example, **human capital** (−22%), **geopolitics** (−25%), and **competitive pressure** (−44%) were significantly downgraded after deliberation. This implies that while participants may have initially overemphasized the role of skilled labor availability, geopolitical tensions, or competitive dynamics, the discussions highlighted more pressing issues related to technical feasibility, regulatory certainty, and cost structures. Likewise, the reduced relevance of the **business case** (−6%) and **subsidies & incentives** (−8%) suggests that while financial considerations remain important, stakeholders recognize that these must be situated within a broader systemic alignment of technological, infrastructural, and regulatory factors. In this way, the collective process mitigated individual biases and shifted attention toward interdependent challenges.

Overall, the before-and-after comparison underscores how structured dialogue helped foster a more nuanced and systemic understanding of transition dynamics. Factors that initially appeared peripheral, such as public perception, ownership costs, and regulatory alignment, gained importance once stakeholders engaged in joint problem structuring. Conversely, factors that were initially emphasized in isolation lost ground, reflecting a calibrated approach of what shapes decision-making in the maritime energy transition when informed by multiple perspectives. These results highlight the value of participatory approaches in combining stakeholder perspectives and exposing interdependencies that may be overlooked when actors evaluate transition challenges individually.

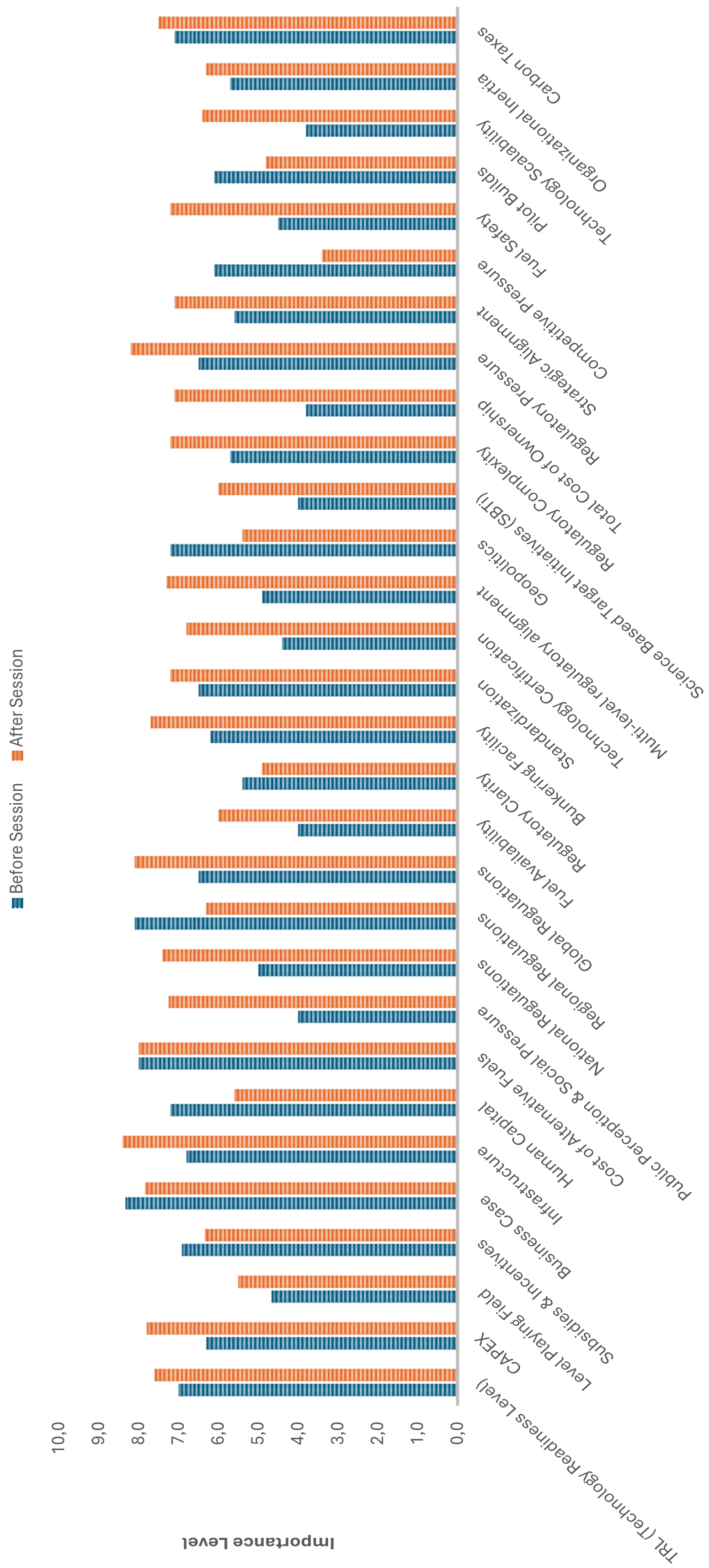

Figure 2: The 30 most occurring factors across 5 sessions.

5. Findings: A System View of Zero-Emission Shipping Adoption

Figure 3 presents the overall system view of factors influencing the adoption of zero-emission shipping (ZES). It illustrates how technological, economic, organizational, and institutional factors interact dynamically to shape adoption outcomes. The model consolidates insights from the Group Model Building sessions and represents over 40 key factors and their interlinkages. Rather than depicting all 250 factors identified during the workshops, this consolidated system view focuses on the main feedback structures that drive or constrain adoption. The model provides an overview of how shifts in one part of the system, such as a change in regulation, technological progress, or cost dynamics, can propagate through other components, ultimately influencing the pace and direction of adoption across the maritime ecosystem.

Within this system, five interrelated sub-systems have been identified, encompassing nine reinforcing and one balancing feedback loop. Each sub-system captures a distinct yet connected domain of influence, including regulatory and institutional alignment, technological innovation and scaling, financial and market incentives, and organizational culture and leadership. The system view makes visible how the maritime transition toward zero-emission operations is not driven by any single factor but by the co-evolution of multiple drivers and barriers acting simultaneously. It highlights the systemic dependencies between technological readiness, regulatory clarity, financial feasibility, and organizational engagement, illustrating that progress in one domain often depends on advancement in others.

The feedback loops shown in Figure 3 provides an overview of how different factors within the system interact and influence the overall adoption over time. Reinforcing loops captures processes that can strengthen the momentum of adoption, where progress in one area supports improvements in others, creating cumulative effects across the system. In contrast, the single balancing loop reflects mechanisms that may slow or stabilize progress when specific barriers or capacity limits are reached. Together, these loops illustrate how the system continually adjusts. This balance between accelerating and moderating forces highlights the complex and adaptive nature of the transition toward zero-emission shipping, where changes in one domain can produce ripple effects across the wider maritime ecosystem.

Overall, the system-wide model underscores that adoption of zero-emission shipping is an emergent outcome of interconnected dynamics rather than isolated actions. It emphasizes that effective progress requires coordination across stakeholders, consistency in regulatory signals, technological scalability, and viable financial pathways. By visualizing these interdependencies, the model provides a shared understanding of where leverage points lie, where targeted interventions can amplify positive feedback effects and reduce systemic barriers. The following sub-sections discuss each sub-system in more detail, illustrating how these interconnected feedback loops collectively shape the trajectory of the maritime industry's transition toward zero-emission operations.

5.1. Full System View on factors for adoption of ZES – Aggregating All Sub-systems

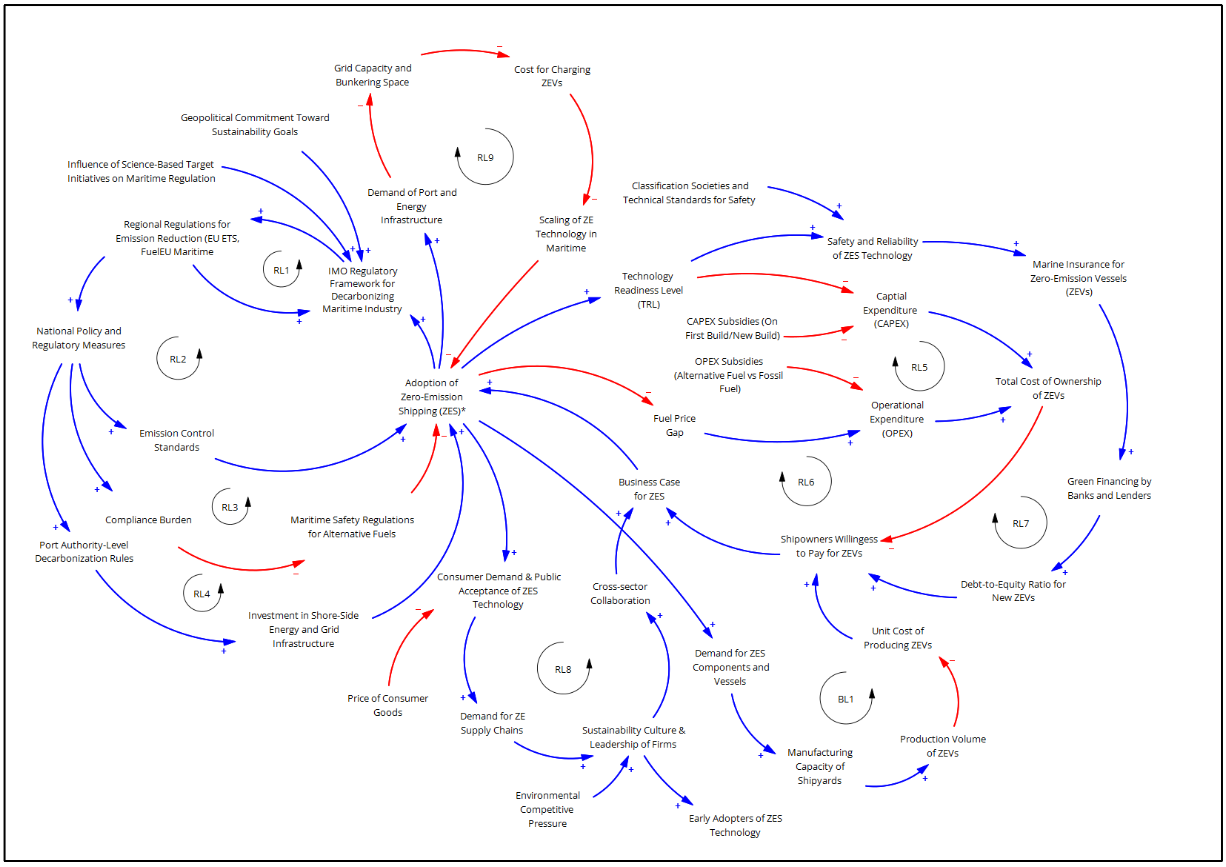

Figure 3: The full system view by aggregating all sub-systems into one exhaustive system.

5.2. Regulatory Alignment Sub-system

As can be seen in Figure 4, the CLD illustrates the structure and dynamics of the regulatory subsystem. The cascading effect of regulation on three separate levels has an impact on the overall adoption of technology. In total the sub-system comprises of four feedback loops, which are all reinforcing, meaning they work to amplify the drivers of decarbonization within the regulatory landscape. The regulatory subsystem plays a pivotal role in shaping the adoption of zero-emission shipping. Regulations evolve and interact across multiple governance levels, including international, regional, national, and port authority, creating a complex, interdependent system that both drives and constrains industry transition. At the international level, geopolitical commitment influences the strength and pace of the International Maritime Organization (IMO) regulatory framework. Strong diplomatic cohesion and alignment among member states reinforce regulatory ambition, while fragmented geopolitical commitment weakens global consensus and delays standard-setting. Growing pressure from industry-led sustainability initiatives also strengthens the IMO's drive to adopt more ambitious emission reduction targets. The four reinforcing loops are explained individually below.

5.2.1. Global-Regional Regulatory Reinforcing Loop (RL1)

When IMO negotiations progress slowly or produce ambiguous outcomes, regional actors such as the European Union tend to accelerate unilateral regulatory action through mechanisms like the EU Emissions Trading System (ETS) and FuelEU Maritime. This dynamic creates a reinforcing loop where international inaction spurs regional acceleration. However, regional initiatives can also feedback positively into the global process, as strong regional measures, supported by robust monitoring and reporting mechanisms, often inform and elevate future IMO standards.

5.2.2. Emission Control Standards Reinforcing Loop (RL2):

As adoption of zero-emission shipping (ZES) progresses, the IMO regulatory framework responds with updated or clarified standards for emission reduction. Stronger international regulations prompt regional actors, such as the European Union, to implement measures like the ETS and FuelEU Maritime. These regional regulations cascade into national policy, leading to the introduction of stricter emission control standards and, in some cases, emission-free zones. By creating operational requirements for ports and vessels, national measures reinforce the adoption of ZES, completing a reinforcing loop where international, regional, and national regulations collectively drive the industry toward decarbonization.

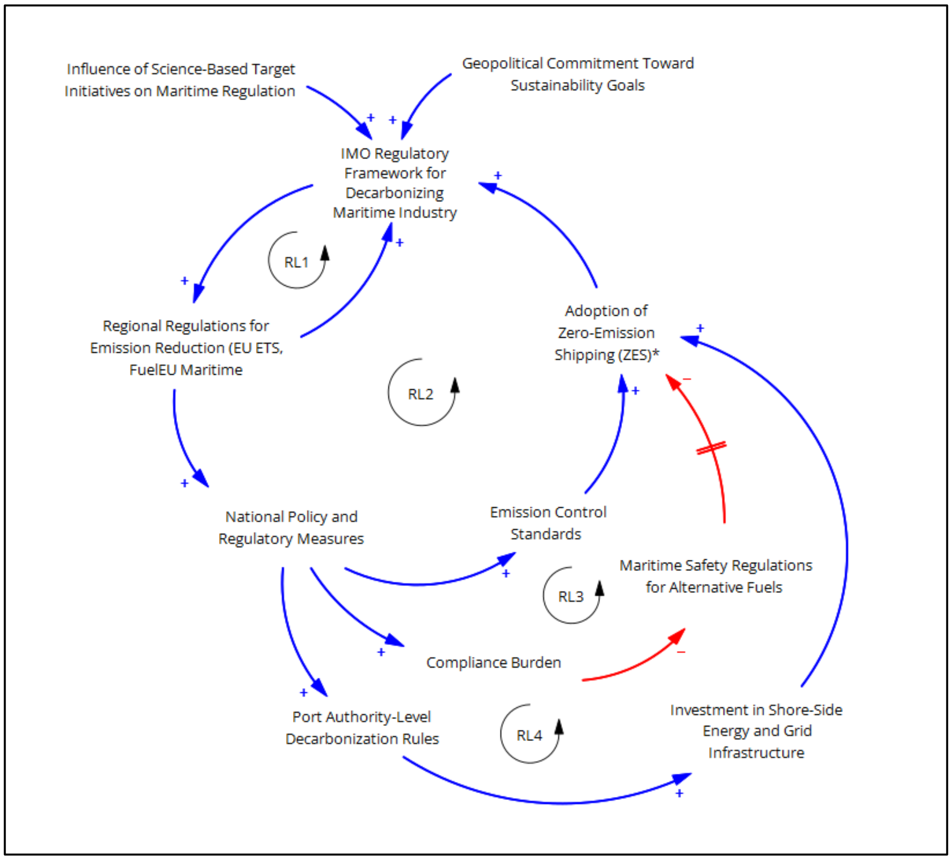

Figure 4: Multi-Level Regulatory Dynamics Shaping Zero-Emission Shipping Adoption.

5.2.3. Multi-level Regulatory Compliance Reinforcing Loop (RL3):

As adoption of zero-emission shipping (ZES) grows, cascading international, regional and national regulations increase the compliance burden on shipowners, including reporting, certification, and operational requirements. Higher compliance complexity slows the adaptation of maritime safety regulations for alternative fuels, which in turn delays vessel approvals. Despite these delays, the loop is reinforcing: the initial increase in adoption triggers stronger regulatory oversight, which eventually strengthens overall system alignment and supports continued industry transition toward zero-emission shipping, even if short-term implementation is slowed by compliance challenges.

5.2.4. Infrastructure Investment Reinforcing Loop (RL4):

Cascading international, regional, and national regulations drive the adoption of zero-emission shipping (ZES) by establishing emission reduction requirements. At the port level, decarbonization rules compel investments in shore-side energy and grid infrastructure, such as electric bunkering, charging stations, and fuel handling systems. Improved infrastructure reduces operational barriers for Zero-Emission Vessels (ZEVs), enabling more vessels to adopt zero-emission technologies. As adoption grows, it reinforces further infrastructure development, creating a self-reinforcing cycle where port-level regulatory measures and infrastructure investment mutually accelerate the transition toward zero-emission shipping.

Together, the four reinforcing loops illustrate how regulatory momentum across governance levels shapes the systemic drivers of zero-emission shipping (ZES) adoption. Global and regional regulatory dynamics (RL1–RL2) establish the foundation for decarbonization by setting emission standards and creating compliance pressures that compel the industry to adapt. While overlapping frameworks can temporarily heighten the compliance burden and slow immediate adoption (RL3), they ultimately strengthen institutional readiness by pushing for harmonization and improved safety standards. At the operational level, port authority rules and infrastructure investments (RL4) translate regulatory intent into physical enablers that lower adoption barriers and create visible progress in the transition. Collectively, these reinforcing mechanisms demonstrate that sustained policy alignment and infrastructure readiness are central to accelerating the maritime industry's shift toward zero-emission operations.

5.3. Investment and Subsidy Dynamics Sub-system

This sub-system, shown in Figure 5, outlines how subsidies improve the business case for zero-emission shipping by reducing the Total Cost of Ownership (TCO). Financial support is important not only for initial capital expenditure (CAPEX) but also for ongoing operational costs (OPEX). Lowering these costs directly improves the business case for investing in zero-emission vessels. The three reinforcing loops demonstrate how this can create a positive cycle to accelerate adoption of ZES.

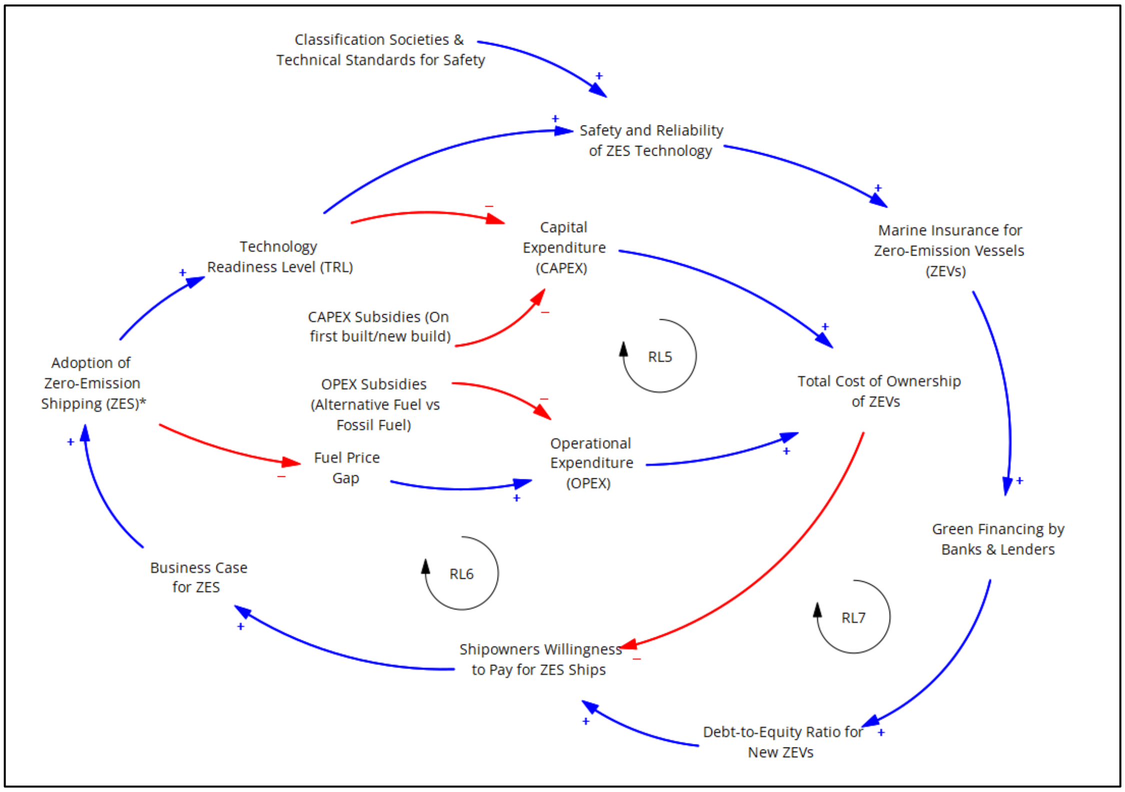

Figure 5: Economic impact of CAPEX and OPEX subsidies on the Total Cost of Ownership.

5.3.1. Capital Cost Reduction through Technology Maturity (RL5):

As more zero-emission vessels (ZEVs) are adopted, technology learning and standardization improve the Technology Readiness Level (TRL). Higher TRL means equipment and systems become more mature and easier to manufacture or install, which lowers capital expenditure (CAPEX). CAPEX subsidies amplify this loop by directly lowering upfront investment costs for first and new builds. By easing the initial financial burden, subsidies help shipowners move faster toward adoption. Lower CAPEX reduces the total cost of ownership (TCO), making ZEVs more financially attractive for shipowners. This strengthens their willingness to invest, improving the overall business case for ZES and driving further adoption of ZES.

5.3.2. Operational Cost Reduction through Fuel Price Convergence (RL6):

As adoption of ZES increases, fuel producers and suppliers scale up production of alternative fuels, narrowing the fuel price gap with conventional marine fuels. This reduces operational expenditure (OPEX) and lowers the total cost of ownership. OPEX subsidies reinforce this loop by offsetting the higher operational costs of zero-emission fuels during the early transition phase. These subsidies make day-to-day operation more viable and maintain competitiveness until

fuel prices naturally converge through market maturity. Reduced OPEX improves shipowners' financial confidence and willingness to pay, which strengthens the business case and accelerates further adoption.

5.3.3. Financial Confidence through Risk Reduction (RL7):

As adoption of zero-emission systems (ZES) increases, the Technology Readiness Level (TRL) of these systems improves. Higher TRL enhances the safety and reliability of zero-emission technology, building confidence among marine insurers. Improved insurance availability and reduced perceived risk make banks and lenders more willing to provide green financing, lowering the debt-to-equity ratio required for new ZEV investments. Easier access to finance increases shipowners' willingness to pay, strengthens the business case for ZES and drives further adoption. This loop shows that technological maturity not only lowers CAPEX but also reinforces financial accessibility.

5.4. Cross-Industrial Collaboration and Sustainability Leadership Sub-system

Figure 6 illustrates how organizational culture and leadership in the maritime industry are influenced by external pressures, particularly consumer demand and public acceptance of new technologies. As demand for cleaner, zero-emission shipping grows, organizations are incentivized to strengthen sustainability-oriented leadership and foster a culture that embraces innovation and cross-industrial collaboration. The sub-system comprises one reinforcing feedback loop that is explained below.

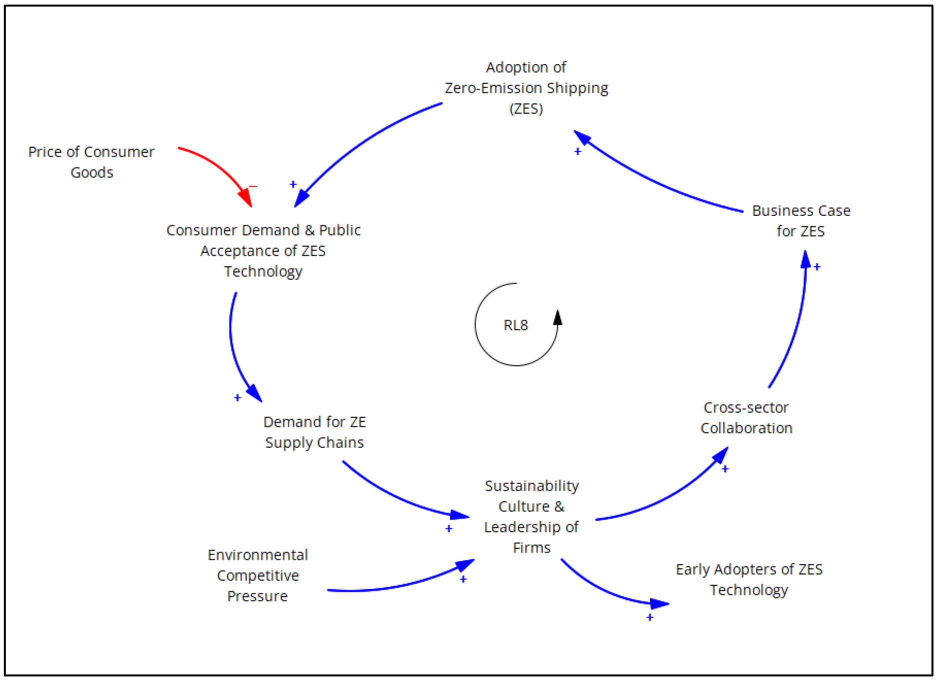

Figure 6: How consumer demand influences the sustainability and culture leadership of organizations to adopt green technology.

5.4.1. Organizational Adaptation and Market Signaling Reinforcing Loop RL8:

This reinforcing loop illustrates how organizational behavior and market perception jointly strengthen the adoption of zero-emission shipping (ZES). As adoption increases, consumer demand and public acceptance of ZES technologies grow, prompting greater demand for zero-emission supply chains. However, higher prices of consumer goods can reduce consumer willingness to support sustainable options, limiting public acceptance. This, in turn, encourages organizations to enhance their sustainability culture and leadership, fostering stronger cross-industry collaboration among shipping companies, cargo owners, ports, fuel and technology providers. Environmental competitive pressure motivates organizations to strengthen sustainability leadership and cultural commitment, making them more likely to act as early adopters of ZES technologies. Such collaboration supports collective problem-solving and investment alignment, reinforcing the business case for ZES and driving further adoption.

5.5. Infrastructure and Production Capacity Dynamics Sub-system

Figure 7 captures the dynamics of technological development and adoption in the maritime industry. It incorporates one reinforcing feedback loop and one balancing feedback loop: the reinforcing loop captures how the adoption of new technologies can lead to further technological developments, while the balancing loop reflects constraints arising from technical, resource, and regulatory limitations. These interactions illustrate how technological progress is shaped by both enabling and limiting factors, which are further detailed in the explanation of each feedback loop.

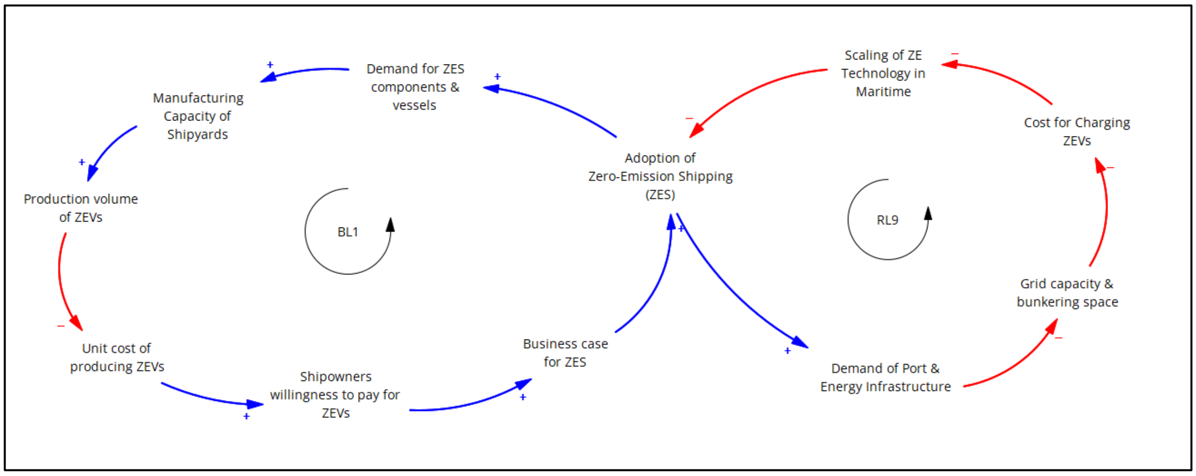

Figure 7: Technological sub-systems showing the consequences of increase in demand of port and energy infrastructure (RL9). The demand for ZES vessels and components driving the price of the technology down (BL1).

5.5.1. Infrastructure Scaling and Cost Reinforcing Loop RL9:

This reinforcing loop demonstrates how the expansion of zero-emission shipping (ZES) strengthens the technological and infrastructural foundation required for its continued growth. As the adoption of ZES increases, demand for port and energy infrastructure rises, placing pressure on existing grid capacity and bunkering space. Initially, limited capacity elevates the cost of charging and refueling zero-emission vessels (ZEVs), constraining short-term scalability. However, as infrastructure investment and grid upgrades respond to growing demand, economies of scale begin to emerge. The improved grid capacity and optimized bunkering networks gradually reduce charging costs, which in turn facilitates broader scaling of zero-emission technologies in maritime operations. Despite the multiple negative links within the loop, the overall effect is reinforcing: each cycle of adoption drives infrastructure expansion and cost efficiency, ultimately accelerating the large-scale viability and diffusion of ZES across the industry.

5.5.2. Production Capacity and Cost Stabilization Balancing Loop BL1:

This balancing loop captures how market growth in zero-emission shipping (ZES) naturally regulates itself through production capacity and cost dynamics. As adoption of ZES increases, demand for zero-emission components and vessels rises, prompting shipyards to expand their manufacturing capacity and increase production volumes. Higher production volumes reduce the unit cost of producing zero-emission vessels (ZEVs) through economies of scale and learning effects, which initially strengthens shipowners' willingness to invest and further supports the business case for ZES. However, as production capacity approaches its limits, the rate of cost reduction diminishes, and supply chain constraints may emerge, slowing further expansion. This negative link between production volume and unit cost introduces a stabilizing force into the system, preventing unchecked growth and bringing the pace of ZES adoption back into balance. The loop thus represents a natural market equilibrium mechanism that keeps the rate of industry transition sustainable and aligned with production and resource capabilities.

6. Stakeholder Group Perspective and Interaction Dynamics

Analysis across six stakeholder groups highlights the distinct perspectives and priorities for adoption of zero-emission shipping. Shipowners and operators tend to focus on financial viability, emphasizing the green premium and limited charterer willingness to pay higher rates, which drives hedging strategies and delays full adoption until infrastructure, regulation, and financing converge. Shipbuilders and system integrators are motivated by owner demand and regulatory compliance but emphasize that technically feasible vessels remain uncompetitive without coordinated financing, certification frameworks, and subsidies addressing both CAPEX and OPEX. Fuel-cell and battery manufacturers stress that technology maturity is not the sole barrier; rather, system readiness, standards, and certification determine whether solutions can scale beyond pilot projects.

Energy suppliers, ports, and infrastructure stakeholders further illustrate the interdependence shaping adoption. Energy suppliers face critical fuel price gaps, requiring predictable demand and supportive OPEX frameworks to justify investment, while ports must balance decarbonization rules with limited bunkering capacity, acting as both enablers and potential bottlenecks. Infrastructure constraints directly influence shipowners' investment decisions, as vessels cannot operate efficiently without reliable energy supply and port facilities. Financial institutions consistently condition their engagement on credible certification frameworks, regulatory clarity, and predictable asset values, reflecting the high-risk perception of zero-emission vessels relative to conventional ships. These dynamics demonstrate how progress in one area is constrained unless corresponding developments occur across the wider system.

Taken together, the findings reveal a network of interdependencies where no single stakeholder group can drive adoption alone. For instance, shipowners wait for infrastructure and finance, ports require demand certainty, suppliers seek supportive policies and contracts, and financiers rely on standards and risk clarity. The multitude of requirements highlights the need for coordinated action across financial, technological, organizational, and institutional dimensions for (systemic) decision-making and action. Achieving adoption at scale requires synchronizing these interlinked factors so that incentives, infrastructure, technology readiness, and regulation advance together, enabling the maritime industry to transition toward zero-emission shipping.

7. Managerial and Policy Implications

The findings of this research highlight that the adoption of zero-emission shipping requires managing the system as a whole rather than focusing on isolated factors. The causal loop analysis and stakeholder interactions reveal a high degree of interdependence between technological, financial, regulatory, and organizational factors, demonstrating that progress in one area requires complementary advances across the system. For managers, policy makers and decision makers this emphasizes the need to adopt a more holistic perspective, understanding how decisions related to fleet investment, technology deployment, infrastructure readiness, and regulatory compliance influence and are influenced by other actors in the maritime ecosystem.

A critical insight emerging from the study is the importance of infrastructure-first prioritization. Early investments in port bunkering facilities, shore-side energy systems, and fuel supply chains can unlock private investment by reducing perceived operational and financial risks. Similarly, safety standards and credible certification frameworks serve as critical enablers, particularly for technology providers and financiers, by creating predictable conditions that support scaling and investment confidence. Regulatory alignment across international, regional, and national levels further reinforces this effect by providing clear and consistent market signals. Managers and policy makers across shipowners, shipbuilders, fuel suppliers, and infrastructure providers can leverage these findings to coordinate priorities, align investment timing, and ensure that operational and technological readiness match regulatory requirements, thereby reducing adoption delays caused by uncertainty or misaligned incentives.

The research also underscores the value of cross-stakeholder coordination and adaptive experimentation. Public–private partnerships, joint innovation platforms, and collaborative pilot projects can help overcome fragmentation, align incentives, and distribute risks more effectively. Stakeholders can use systemic insights to identify critical interdependencies, such as the link between financing availability, regulatory clarity, infrastructure readiness, and technology scalability.

Building on these insights, the next steps for this research involve translating the system-level understanding into actionable and testable strategies. One important direction is to develop a quantitative stock & flow simulation model that converts the current static causal loop structure into a dynamic representation of the transition process. Such a model would allow researchers, managers, and policymakers to explore how changes in technology costs, regulatory incentives, or infrastructure investment could influence the rate of zero-emission adoption over time through a simulation. Another avenue is to use the model for policy and investment scenario analysis, examining how alternative regulatory frameworks, funding mechanisms, or technology pathways affect adoption dynamics. In addition, insights from this study can be extended to identify which factors most strongly influence business model, helping organizations reconfigure their value creation and capture mechanisms in response to the energy transition. Similarly, the findings can shed light on the factors that shape organizations' intentions to invest in green technologies, providing a behavioral and strategic perspective on adoption decisions. Longitudinal studies could also help track how organizational learning, collaboration patterns, and market responses evolve as technologies and regulations mature. Together, these steps would support evidence-based decision-making and guide the coordinated actions required to accelerate the maritime industry's transition toward zero-emission operations.

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Questions, suggestions, ideas on this report and/or our research?

We welcome questions, suggestions, or ideas related to this report and the broader research program. This study forms part of an ongoing research initiative aimed at understanding and supporting the transition to zero-emission shipping. Stakeholder feedback is highly valuable in refining the research, validating findings, and identifying areas for further investigation. We encourage readers to share their perspectives, experiences, or recommendations, and to engage with the research team to discuss any aspect of the work. Your input will help ensure that the research remains relevant and aligned with the needs of the maritime industry.

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