

# Closing the Loop: Policy, Technology, and Economic Drivers for a Circular Maritime Economy

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**Abstract:** The maritime industry's traditional "build-operate-dispose" approach has become unsustainable, causing significant resource depletion and waste. Although the Circular Economy (CE) presents a viable alternative, its adoption in the maritime sector remains fragmented and slow. This lag stems from the industry's tendency to address policy, technology, and economic challenges separately, rather than as interdependent components of a unified system. A deeper understanding of how these dimensions interact is essential for enabling a holistic transition to circularity.

This research aims to develop an integrated framework that highlights the interconnections among policy, technology, and economic factors in advancing a circular maritime economy. By demonstrating that regulatory measures, technological innovation, and business models must evolve together, the study seeks to establish circular practices as both standard and economically advantageous.

Using a qualitative, conceptual approach grounded in systems thinking, the research synthesizes findings from scholarly literature, industry analyses, and policy reports to map these interrelations. The resulting framework will identify high-impact intervention points—such as how policies mandating digital material passports (policy) can enable advanced asset tracking (technology), making remanufacturing more viable and profitable (economics).

The study offers actionable insights for policymakers, industry leaders, and investors. It proposes strategies for designing policies that stimulate innovation and for businesses to capitalize on circular economic opportunities. Aligned with the themes of Business Innovation and Sustainable Development, this research provides a cohesive roadmap for transforming the maritime sector into a model of circular resource management.

**Keywords:** *Circular Economy, Maritime Policy, Sustainable Technology, Economic Incentives, Systems Thinking, Business Models.*

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## I. INTRODUCTION

### ➤ *Background and Context*

The maritime sector is integral to global supply chains, managing over 80% of international trade by volume (UNCTAD, 2023). However, the "take, make, dispose" linear economic paradigm which is increasingly unsustainable, is largely responsible for this vital economic function. This methodology results in excessive resource extraction, waste generation, and environmental degradation, particularly at the conclusion of a vessel's lifecycle, where shipbreaking frequently occurs under substandard conditions, leading to significant ecological and social challenges (Shin et al., 2023). In response to these issues, the concept of a circular economy (CE) has surfaced as a transformative strategy aimed at eradicating waste and assuring the recycling, remanufacturing, and reuse of materials (Kirchherr et al.,

2023). Shifting to a circular model is not merely an environmental imperative for the maritime industry; it is also a strategic initiative for its long-term viability and alignment with the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production).

### ➤ *Problem Statement*

Despite the acknowledged potential of CE principles, the maritime industry has been sluggish in achieving substantial advancements. A significant obstacle is the disjointed approach to instigating change. Policymakers often focus on international regulations such as the Hong Kong International Convention, which primarily emphasizes safe recycling rather than fostering a holistic circular system (Poulakis & Papadakis, 2024). Concurrently, technological

innovations, including digital twins for asset tracking and novel recycling techniques, are frequently developed in isolation, lacking the market demand that cohesive policies or economic incentives could generate (Zhou et al., 2023).

Conversely, innovative circular business models, such as "product-as-a-service," struggle to gain traction in the absence of supportive regulations and the substantial initial investments required for the necessary technologies (Acciaro & Wilmsmeier, 2023). This scenario results in a frustrating cycle of stagnation, where no single element is sufficiently robust to disrupt the entrenched linear system.

#### ➤ *Research Gap*

The various facets of this shift have been thoroughly studied in the literature as of late. There is a considerable amount of research on maritime environmental policies (such as the Hong Kong Convention), the sustainability potential of specific technologies (including IoT and blockchain), and the theoretical appeal of circular business models. However, there is still a significant knowledge vacuum regarding the ways in which these elements interact and work together. Numerous studies tend to analyze these drivers in isolation, overlooking the broader context of how they can be strategically coordinated to promote a self-reinforcing cycle of transformation. We currently lack a unified model that demonstrates how a change in policy can ignite technological innovation, which subsequently can create new economic value and, ultimately, generate political momentum for additional policy developments. This gap leaves both practitioners and policymakers without a clear, systematic framework for action.

#### ➤ *Research Objective*

This study aims to bridge that gap by developing and releasing an integrated Policy-Technology-Economics (P-T-E) framework for a circular maritime economy. The main goal is to show that only by bringing these three crucial factors into synergy would the transformation be hastened.

#### ➤ *Research Questions*

To guide this research effectively, we have outlined several pivotal questions:

- RQ1: In what ways are policy, technology, and economic drivers functioning independently, and what difficulties does this disjointed approach present for realizing a circular maritime economy?
- RQ2: What vital connections and feedback mechanisms exist among policy, technology, and economic drivers that we can leverage for a self-sustaining transition?
- RQ3: What targeted strategies can policymakers, industry leaders, and technology providers adopt to foster this collaborative alignment and address current challenges?

#### ➤ *Significance and Contributions*

This research offers numerous distinctive contributions. Theoretically, it expands the boundaries of the field by transcending a fragmented analysis to propose a novel, integrative framework that captures the interconnected essence of the maritime circular economy transition. It

enriches the existing literature on socio-technical transitions and systems thinking within the maritime domain. Practically, it provides a pragmatic blueprint for industry stakeholders shipowners, OEMs, recyclers, and investors to identify strategic leverage points and align their investments and business models with contemporary policy and technological advancements. From a policy perspective, the results furnish regulators with a coherent, evidence-based approach for developing comprehensive policy packages that effectively stimulate innovation and market growth, rather than depending on generic mandates.

#### ➤ *Structure of the Paper*

Following this introduction, the paper is organized in a coherent manner. In Section 2, we engage in a literature review that critiques the disjointed approach of contemporary research concerning policy, technology, and economics. Section 3 delineates the systems thinking methodology that contributed to the development of the P-T-E framework. Subsequently, in Section 4, we present the framework itself and examine the significant interconnections and feedback loops it encompasses. The study's findings are presented in Section 5, which also highlights particular policy implications and offers ideas for future study directions.

## II. LITERATURE REVIEW

Transitioning to a circular economy (CE) within the maritime sector presents a multifaceted challenge that has been approached from various, often disjointed, academic and professional perspectives. By critically assessing the three essential pillars required for this shift, this review aims to compile the body of information already in existence: the policy-regulatory framework, technological enablers, and economic-business drivers. The primary conclusion here is that although each pillar has been extensively analyzed independently, the essential connections among them remain largely neglected in the literature, leading to a fragmented comprehension that obstructs advancement.

#### ➤ *The Technological Pillar: Enablers Without a Pull Mechanism*

An increasing amount of research is exploring the technological advancements that can facilitate a circular economy within maritime settings, frequently adopting an optimistic perspective regarding the role of technology.

#### • *Key Theories and Models:*

A significant portion of this research is contextualized within technological innovation systems and the contemporary term "Industry 4.0." It investigates how digital and engineering technologies can lead to circularity (Zhou et al., 2023).

#### • *Major Findings:*

Scholars have identified a variety of promising technologies. These encompass digital solutions such as IoT sensors and blockchain for asset tracking and ensuring material provenance, which are vital for enabling reuse and remanufacturing (Kouhizadeh et al., 2024). Furthermore, progress in material science and recycling techniques,

including laser sorting for metals and chemical recycling for composites, is recognized for its potential to improve the quality and efficiency of material recovery (Dev et al., 2024).

• *Limitations and Gaps:*

A notable shortcoming in this technological discourse is the prevalent assumption that "if we build it, they will come." Numerous studies concentrate on the technical specifics and potential benefits but frequently neglect the economic viability and the barriers to market acceptance. The existing literature often fails to address the critical question: If there is no robust regulatory framework or a validated business model in place, it will be very difficult to fund these technologies? This results in a "technology push" environment lacking a corresponding "market pull," leaving many innovations trapped in pilot projects and theoretical discussions.

➤ *The Economic and Business Model Pillar: Investigating Viability*

The third pillar of the literature examines the economic elements involved, focusing on the business justification for adopting circularity.

• *Key Theories and Models:*

This domain draws upon principles from business model theory, transaction cost economics, and finance. It explores how value can be created and captured within a circular paradigm, transcending the traditional model of merely selling products (Bressanelli et al., 2023).

• *Major Findings:*

Studies have revealed numerous innovative circular business models within the maritime industry, including product-as-a-service (for instance, offering "power-by-the-hour" for engines instead of selling the engines outright), performance-based contracts, and using waste from one process as input for another is known as industrial symbiosis (Acciario & Wilmsmeier, 2023). These investigations suggest that such models can align the incentives of manufacturers with the durability and recyclability of products. Nonetheless, the literature consistently highlights considerable obstacles: substantial initial costs, perceived risks, and a scarcity of financing options tailored for circular investments.

• *Limitations and Gaps:*

The economic literature frequently presumes the policy and technological environment as a constant or an external factor. While it underscores the importance of a robust business case, it inadequately addresses how that case is collaboratively influenced by supportive policies (such as green procurement and extended producer responsibility) and enabling technologies that assist in reducing transaction costs. The issue of alleviating risks for private investors in the absence of strong regulatory signals remains largely overlooked.

➤ *Bridging the Gaps: The Disconnected Triad*

Upon reflection on the three foundational pillars of literature, it becomes evident that a notable disconnect exists. Table 1 offers a concise overview of this critical analysis.

Table 1 Critical Gaps in the Literature on Maritime Circular Economy

Pillar	Primary Focus	Key Limitation	Implication
Policy & Regulation	International governance, compliance, and risk mitigation.	Fails to actively stimulate markets or innovation; operates in silos.	Creates a framework for "less bad" practices but not for "doing good."
Technology & Innovation	Technical feasibility and potential of digital and engineering solutions.	Assumes market adoption without addressing economic viability or regulatory drivers.	Results in a portfolio of promising but underutilized technologies.
Economic & Business Models	Value creation, profitability, and investment barriers.	Treats policy and technology as externalities, not integral to the business case.	Identifies the "what but not the "how" of achieving financial viability.

Source: (Author, 2025)

The most prominent gap is the lack of research that effectively models the synergistic interactions and feedback loops among these three pillars. Although the literature thoroughly examines each domain, it frequently overlooks the overarching connections. For example, there is no cohesive framework that demonstrates how a carbon tax (policy) can enhance the financial attractiveness of remanufacturing (technology), which could subsequently lead to increased investment in recycling R&D (technology), thereby establishing a positive feedback loop. By putting out an integrated Policy-Technology-Economics (P-T-E) paradigm, this study aims to close that gap. It asserts that progressing towards a circular maritime economy involves not merely advancing each pillar independently, but rather

strategically aligning them to cultivate a self-reinforcing system.

**III. METHODOLOGY**

This study employs a qualitative research design aimed at developing a conceptual framework through systems thinking. This methodology is crucial for addressing the intricate, interconnected nature of the policy-technology-economics (P-T-E) nexus within the maritime circular economy. Given that the objective is to investigate relationships and synergies rather than to validate a specific hypothesis, this approach is particularly appropriate for theory-building in emerging research domains where

variables are interdependent and context-sensitive (Gregor & Hevner, 2013; Midgley, 2000).

#### ➤ *Research Design and Philosophical Approach*

The study is based on a system thinking perspective, which emphasizes the interconnections among various components of a system and the evolution of these systems over time, particularly within the context of larger systems (Meadows, 2008). This philosophical stance is consistent with critical realism, as it seeks to reveal the underlying structures and mechanisms, the driving forces behind policy, technology, and economics that shape observable events in the maritime sector (Sayer, 2000). This design was chosen because the transition to a circular economy is not a simple process; it represents a complex systemic change that requires an analytical framework capable of addressing feedback loops, non-linear interactions, and emergent behaviors.

#### ➤ *Data Sources and Collection Procedure*

This research is founded on a comprehensive and systematic analysis of secondary data aimed at developing and validating the P-T-E framework.

#### • *Systematic Literature Review:*

We commenced with a systematic literature review (SLR) to establish a robust foundation and identify the critical components and interactions within each pillar. We followed the prescribed procedure as outlined by Tranfield et al. (2003).

#### • *Databases and Search String:*

We executed searches in Scopus, Web of Science, and Google Scholar, employing a combination of keywords: ("circular economy" OR "sustainable shipping") AND ("maritime policy" OR "regulation") AND ("technology" OR "innovation") AND ("business model" OR "economic driver" OR "investment").

#### • *Inclusion/Exclusion Criteria:*

Our search was concentrated on peer-reviewed journal articles, books, and official reports from international organizations (such as the IMO and World Bank) published between 2000 and 2024. We began with over 500 publications, which we refined based on their relevance to the three core pillars, ultimately selecting 95 key sources for an in-depth examination.

#### • *Analysis:*

We scrutinized the literature to identify key themes, barriers, enablers, and proposed solutions within each domain (policy, technology, economics), as well as any connections that were referenced but not thoroughly investigated.

#### • *Document Analysis of Policy and Industry Reports:*

To ensure our analysis accurately reflects contemporary practices, we conducted a meticulous document analysis of significant policy frameworks (including the Hong Kong Convention, EU Green Deal, and IMO's Initial GHG Strategy) and industry reports from leading consultancies and classification societies (such as DNV and the Maersk McKinney Moller Center). This enabled us to comprehend the

real-world context of the regulatory environment and the challenges encountered by the industry.

#### ➤ *Analytical Framework and "Variables"*

Rather than concentrating exclusively on quantitative variables, this research delves into the systemic elements and the nature of the relationships they maintain. These components act as the analytical units within the P-T-E framework.

#### • *Core Components (The Pillars):*

- ✓ **Policy Drivers:** This encompasses mechanisms such as international agreements, carbon pricing, extended producer responsibility (EPR), and environmentally conscious public procurement.
- ✓ **Technology Enablers:** This category includes innovations like digital twins, blockchain for traceability, advanced recycling technologies, and sustainable ship design.
- ✓ **Economic Drivers:** In this section, we examine factors such as circular business models (Product-as-a-Service), investment evaluation criteria, total cost of ownership, and the demand for secondary materials in the market.

#### • *Relationship Types (The Interconnections):*

The analysis focuses on identifying and classifying the interactions among these components:

- ✓ **Enabling/Constraining:** This aspect investigates how one driver can either support or obstruct another (for example, how policy can encourage technological adoption by mitigating risk).
- ✓ **Reinforcing/Balancing Feedback Loops:** These represent the vicious or virtuous cycles that can either accelerate or decelerate change within the system (such as how a successful circular business model can generate economic validation, which subsequently fosters political support for favorable policies).
- ✓ **Direct/Indirect Effects:** This pertains to the primary and secondary consequences that an intervention in one pillar may exert on the others.

#### ➤ *Data Analysis and Framework Development Techniques*

The creation of the P-T-E framework was a back-and-forth journey that relied on two main qualitative techniques:

#### • *Thematic Analysis:*

We took the data from the systematic literature review (SLR) and document analysis and coded it using a blend of methods—both deductively (starting with the three pillars as our initial codes) and inductively (allowing new themes to surface and reveal their connections). This process followed the structured steps laid out by Braun and Clarke (2006): getting familiar with the data, generating initial codes, searching for themes, reviewing those themes, defining and naming them, and finally producing the analysis. We used NVivo 12 software to help manage the coding process.

#### • *Causal Loop Diagramming (CLD):*

To illustrate the dynamic relationships we uncovered through thematic analysis and Causal Loop Diagrams

(CLDs). To illustrate the dynamic relationships, we uncovered through thematic analysis and Causal Loop Diagrams (CLDs). These diagrams, which illustrate feedback loops and show the causal relationships between various variables, are crucial tools in systems dynamics (Sterman, 2000). These tools and techniques were used to:

- ✓ Map the current "as-is" system that sustains the linear economy.
- ✓ Model the envisioned "to-be" system based on the P-T-E framework, pinpointing key leverage points for intervention.
- ✓ We specifically chose this method because it effectively shows how a change in one driver (like a new policy) can create ripple effects throughout the technological and economic landscape.

➤ *Tools for Analysis*

We utilized the following software tools to aid our analysis:

- NVivo 12: For coding and conducting thematic analysis of the qualitative data gathered from the literature.
- Lucidchart: To design the Causal Loop Diagrams and visual representations of the P-T-E framework.

➤ *Justification and Limitations*

The methodology we have selected is highly appropriate for achieving our research objectives. The development of qualitative frameworks and systems thinking are acknowledged methods for addressing the intricate "wicked problems" that are marked by a wide range of stakeholders, high levels of complexity, and uncertainty (Head & Alford, 2015).

By employing Causal Loop Diagrams (CLDs), we establish a transparent and reproducible method for modeling the intricate cause-and-effect relationships that quantitative approaches may oversimplify.

A significant limitation of this study is its primarily conceptual nature. The P-T-E framework has been formulated and validated through theoretical approaches, drawing on existing literature and logical reasoning, yet it has not undergone empirical testing with quantitative data or real-world case studies. The feedback loops identified in the CLDs are derived from literature and logical deduction rather than direct empirical measurement. Furthermore, although our literature review is systematic, it may not encompass every conceivable perspective.

Notwithstanding these limitations, they create opportunities for future research, which we will elaborate on in the conclusion. This forthcoming work can shift from constructing conceptual models to empirically validating them through case studies, system dynamics modeling, and quantitative analysis.

**IV. RESULTS AND DISCUSSION**

In this section, we will explore the principal findings of our research: the integrated Policy-Technology-Economics (P-T-E) framework designed to promote a circular maritime economy. The results are derived from our systematic literature review and systems analysis, and we will examine them collectively to provide a more profound understanding of how these elements interact each other to create a self-reinforcing system for change.

➤ *The Integrated P-T-E Framework: A System of Synergistic Drivers*

The primary conclusion drawn from this research is the establishment of the P-T-E framework, which transitions from a limited viewpoint to depict the dynamic interrelations among the three principal drivers. The transition towards a circular maritime economy is not a simple process; instead, it arises from the cooperative interactions among these domains as demonstrated in Figure 1.

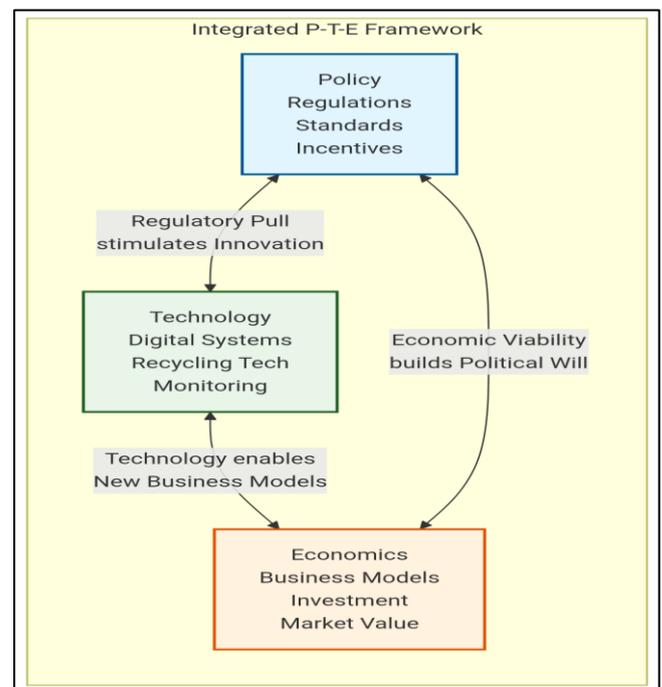


Fig 1 The Integrated Policy-Technology-Economics (P-T-E) Framework for a Circular Maritime Economy  
Source: (Author, 2025)

The analysis reveals that each interaction within this framework paves the way for significant transformations:

- *The Policy-Technology Nexus (The "Regulatory Pull"):*  
According to the findings, well-crafted rules can serve as strong inducements for technological advancement in addition to serving as barriers. For instance, the introduction of a transparent carbon pricing mechanism (Policy) substantially alters the economic environment, rendering it financially viable to invest in energy-efficient ship designs and waste-minimizing recycling technologies (Technology). Conversely, in the absence of such policies, a market failure occurs, resulting in these technologies being neglected. This

nexus generates a "pull" effect, where regulatory signals mitigate risks and steer private R&D investments towards circular solutions, thereby reinforcing the theoretical perspectives of Acciaro & Wilmsmeier (2023) concerning the need for market-correcting instruments.

• *The Economics-Policy Nexus (The "Proof-of-Concept" Feedback):*

A notable observation is the robust feedback loop that exists between economics and policy. The analysis indicates that political will frequently depends on evident economic success. For example, when circular business models, such as performance-based contracting for ship propulsion systems, exhibit profitability (Economics), they cultivate influential industry coalitions that advocate for supportive and stable policies (Policy). This acts as the "proof-of-concept" that can overcome political inertia and present a compelling argument for increasing regulatory support, moving away from the traditional perspective of policy as merely a top-down influence.

➤ *Identifying Reinforcing Feedback Loops for Systemic Change*

Going beyond mere interactions, the systems analysis utilizing Causal Loop Diagramming (CLD) has identified critical reinforcing feedback loops (R loops) that can accelerate the transition. Figure 2 illustrates the most significant of these loops.

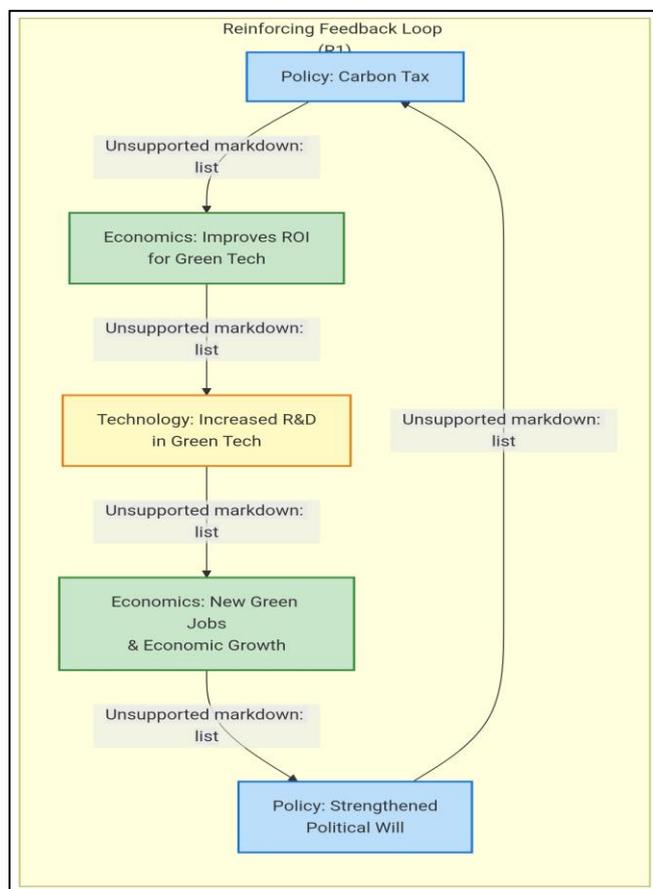


Fig 2 Causal Loop Diagram of a Reinforcing Feedback Cycle (R1)

Source: (Author, 2025)

✓ *Description:*

This diagram illustrates the self-reinforcing feedback loop that accelerates the transition to a circular maritime economy. The cycle begins with policy intervention (Carbon Tax), which creates economic incentives that drive technological innovation. This innovation, in turn, generates positive economic outcomes (jobs and growth), which build political support for further policy action. The "+" signs on all arrows indicate reinforcing relationships where an increase in one element leads to an increase in the next, creating a virtuous cycle of sustainable development.

• *The Color Coding Maintains Consistency with Figure 1:*

- ✓ Blue: Policy-related elements
- ✓ Green: Economics-related elements
- ✓ Yellow: Technology-related elements

➤ *Discussion: Connecting the Framework with Current Challenges and Opportunities*

The true power of the P-T-E framework lies in its ability to identify the fundamental causes of our present stagnation and to underscore critical areas where significant improvements can be made.

• *Analyzing the Present Context: The Cycle of Inaction*

We can examine the current linear system through the perspective of the P-T-E framework, which uncovers a trend of weak or misaligned interactions. For example, consider the ineffective recycling policies (Policy) that do not promote a market for advanced recycling technologies (Technology). This scenario results in elevated costs for green recycling (Economics). Ironically, this high expense is frequently cited as a justification for not enhancing the very policies that could have spurred the technological innovations necessary to lower those costs initially. This leads to a frustrating cycle, or this research moves the discourse from what needs to be done to how the different pieces of the puzzle can be made to fit together to create a self-sustaining transition.

V. CONCLUSION

This research sought to address a critical and persistent challenge: the sluggish advancement towards a circular economy within the maritime sector. The central premise was that the existing, disjointed methodology where policy, technology, and economic elements are developed in isolation—significantly contributes to this stagnation. In order for the transition to be as a comprehensive, interconnected process, the study proposed an integrated Policy-Technology-Economics (P-T-E) framework.

A primary insight from this research is that the pathway to a circular maritime economy is not linear; rather, it is influenced by a network of dynamic interrelations and reinforcing feedback mechanisms. The study effectively demonstrated how particular policies (such as carbon pricing and digital passport mandates) generate a "regulatory pull" that propels vital technological progress. Furthermore, it illustrated that these innovations can facilitate sustainable circular business models by reducing costs and risks, thereby

providing the "economic justification" necessary to sustain ongoing political backing for more ambitious policies. This addresses the principal research inquiries by showing that the challenges associated with fragmented approaches (RQ1) can be overcome by leveraging the distinctive interconnections and feedback mechanisms among the P-T-E drivers (RQ2).

The significance of this research lies in its novel theoretical contribution. It transcends the mere enumeration of barriers and solutions to present a holistic systems-level framework that elucidates the mechanisms of change. By integrating concepts from systems thinking and socio-technical transitions within maritime studies, this research offers a fresh lens for diagnosing inertia and identifying effective intervention strategies. It underscores a vital shift in perspective, positing that the key to achieving circularity is not solely the strength of individual components, but rather the resilience of the connections that unite them.

It is crucial to acknowledge the constraints of this study. As a conceptual framework informed by qualitative systems analysis, its concepts, although grounded in existing literature and rational reasoning, require validation in practical contexts. Subsequent research should focus on quantitatively evaluating the suggested feedback loops through system dynamics modeling, complemented by comprehensive case studies of policies or business models that demonstrate the P-T-E synergies in practice. Notwithstanding these drawbacks, the study offers a strong and convincing framework, suggesting that the marine industry must first overcome the conceptual and practical gap between economics, technology, and policy in order to properly "close the loop."

#### A. Policy Implications and Future Research Directions

The P-T-E framework provides a strong foundation for strategic initiatives among diverse stakeholders in the maritime sector. The ensuing recommendations are designed to translate theoretical insights into practical actions for implementation.

##### ➤ Policy Implications

- *For International Regulators (IMO, EU) and National Governments:*

##### ✓ *Formulate Comprehensive Policy Packages:*

It is crucial to move beyond isolated policies. Take the Hong Kong Convention as an example; it should be complemented by initiatives that promote circularity, such as a "Green Ship Recycling Fund." This fund could be financed through a nominal fee on maritime transport, which would subsequently support certified green recycling initiatives. Concurrently, we should mandate Digital Product Passports for newly constructed ships to ensure effective tracking of technology for both regulatory compliance and market advancement.

##### ✓ *Establish Technology-Forcing Regulations:*

It is imperative to define clear, long-term standards that stimulate innovation. This entails setting a timeline for more stringent carbon intensity standards (CII) that not only

foresee but also necessitate the development of new technologies. Furthermore, we should incorporate "Design for Disassembly" principles into the classification rules for vessels.

##### ✓ *Leverage Procurement as a Market Catalyst:*

Public procurement of shipping services, such as state-operated ferries and naval auxiliaries, can serve as a significant leverage point. Requiring vessels with validated circular credentials will allow us to create a stable market for innovators.

- *For Industry Stakeholders (Shipowners, OEMs, Financiers):*

##### ✓ *Establish Cross-Value Chain Consortia:*

Industry leaders ought to take the lead in forming consortia that can pilot integrated P-T-E solutions. For instance, a partnership between a shipowner, an engine OEM, and a recycler could explore a "power-by-the-hour" service model, underpinned by a shared digital asset passport, demonstrating its economic feasibility to policymakers.

##### ✓ *Embrace Total Cost of Ownership (TCO) Models:*

It is vital to extend the focus beyond mere initial capital expenditure (CAPEX). Shipowners and financiers should adopt TCO models that account for end-of-life residual value, potential carbon liabilities, and recycling expenses. This strategy will inherently encourage circular designs and business models.

##### ✓ *Investing in Data Infrastructure:*

It is crucial to regard data as a significant asset. Allocating funds towards IoT and data management systems for a Digital Product Passport transcends mere compliance costs; it represents a strategic approach to harness future advantages through circular services and enhanced asset valuation.

- *Future Research Directions*

This conceptual study opens up several significant avenues for forthcoming empirical and applied research:

##### ✓ *Quantitative System Dynamics Modeling:*

The proposed feedback loops (such as the "Green Investment Virtuous Cycle") ought to be transformed into a quantitative system dynamics model. This would allow researchers to simulate various policy scenarios (including different carbon tax rates) and forecast their impacts on technology adoption and economic outcomes.

##### ✓ *Empirical Case Studies:*

There is a need for comprehensive case studies to investigate existing, albeit isolated, instances of circular practices (for example, a particular remanufacturing supply chain for a marine component) through the P-T-E framework. This would yield real-world evidence of the framework's efficacy and underscore specific implementation challenges.

✓ *Governance and Standardization Research:*

An essential domain for future inquiry is the multi-stakeholder governance required for a holistic Digital Product Passport. Research should concentrate on proposing viable models for data ownership, sharing protocols, and international standards.

✓ *Behavioral and Organizational Studies:*

Future investigations should examine the behavioral and cultural barriers within maritime organizations that hinder the adoption of circular business models and collaborative approaches, exploring strategies to facilitate organizational change.

By adopting this integrated P-T-E perspective and investigating these research avenues, stakeholders can transform the circular economy from a commendable goal into a tangible reality, thereby ensuring the maritime industry's enduring sustainability and resilience.

### ETHICAL DECLARATIONS

➤ *Ethical Approval:*

This study does not involve human participants, human data, or animal subjects. As such, ethical approval was not required.

➤ *Consent to Participate:*

Not Applicable.

➤ *Consent for Publication:*

Not Applicable

➤ *Data Availability:*

No primary datasets were generated or analyzed during the study. The proposed Maritime Asset Passport architecture is conceptual and design-oriented.

➤ *Acknowledgement:*

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➤ *Conflict of Interest*

The author declares that there is no conflict of interest regarding the publication of this paper.

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