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The Eco-Friendly Paradigm Shift in Shipping and Shipbuilding: Policy–Technology Linkages as Key Drivers

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Abstract

The decarbonization of shipping and shipbuilding is a critical challenge under the International Maritime Organization's (IMO) 2030 greenhouse gas (GHG) reduction target and 2050 net-zero strategy, requiring effective coordination between policy and technology. This study investigates how Japan, China, and Korea respond to these regulatory pressures by systematically analyzing their policy–technology linkages. A four-stage design was applied, combining qualitative case studies, policy–technology mapping, theoretical interpretation, and comparative analysis, to trace how national strategies shape eco-friendly transitions. Japan employs an innovation-led, institution-convergent model in which technological demonstrations drive institutional adaptation and diffusion, China follows a policy-designated, execution-oriented model where state-led interventions accelerate commercialization, and Korea adopts a coordination-based, cyclical model balancing public demonstrations, financial support, and international standardization to reduce transition costs. These findings demonstrate that sequencing between policy–technology linkage is context-dependent, shaped by technological maturity, economic feasibility and infrastructure, institutional predictability, and socio-environmental acceptance. The study contributes a cyclic co-evolutionary perspective that moves beyond technological or institutional determinism, reconceptualizes regulation as enabling infra-structure, and identifies implications for global standard-setting and industrial competitiveness. The insights inform practical strategies for major shipbuilding nations to reduce costs while sustaining competitiveness under the IMO's decarbonization framework.

Keywords: maritime decarbonization; eco-friendly ship; IMO GHG strategy; policy–technology interaction; paradigm shift



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1. Introduction

1.1. Background and Necessity of the Study

In the 21st century, the international community has strengthened global governance to address the climate crisis and pursue carbon neutrality, with the International Maritime Organization (IMO) leading the transition toward eco-friendly practices in global shipping and shipbuilding [1]. In 2018, the IMO adopted the Initial IMO GHG Strategy, which set targets to reduce CO₂ emissions per unit of transport work by at least 40% by 2030 and to cut total GHG emissions from international shipping by ≥50% by 2050, compared with 2008 levels [2]. Furthermore, in its 2023 revised strategy, the IMO aimed to achieve net-zero

emissions around 2050 and specified that low- or zero-carbon fuels should constitute at least 5%, and preferably 10%, of the energy mix by 2030 [3].

Consequently, IMO-driven environmental regulations on ship-source pollution have made decarbonization an obligation rather than a choice for the shipping and shipbuilding industries, necessitating strategic intervention at the national level. Since 2020, major maritime nations have invested heavily in eco-friendly ship fuels and related technologies [4]. For example, Japan, through its Green Innovation (GI) Fund, promotes demonstrations of hydrogen and ammonia fuel engines and the development of bunkering infrastructure, illustrating how subsidies can drive technological adoption [5]. Meanwhile, China, through the 2024 edition of the Green Technology Promotion Catalog, strategically designated LNG, SCR aftertreatment, electric propulsion, and waste-to-resource technologies, thereby accelerating commercialization through institutional prioritization [6].

In this context, technological determinism states that technological progress drives legal and institutional change, whereas institutional determinism emphasizes that subsidies and regulations shape technological choices and restructure industrial systems [7]. Thus, a critical question arises: have eco-friendly policies in Japan, China, and Korea driven technological innovation, or has technological progress compelled policy change? Addressing this causal issue offers insights into the relationship between policies and technologies in maritime decarbonization. Given the binding transition pressures of the IMO's 2030 and 2050 net-zero targets, analyzing policy–technology interactions across these countries is an essential academic task.

1.2. Literature Review

The relationship between technology and society has long been framed by contrasting perspectives of technological determinism (TD) and the social shaping of technology (SST). Bimber (1990) [8] clarified the concept by distinguishing norm-based, unintended consequences, and logical sequence accounts, ultimately concluding that Marx's views on production forces positioned technology as a facilitator rather than an autonomous determinant of social change. Williams and Edge (1996) [9] advanced SST by emphasizing that innovation processes are patterned by social and economic factors as well as technical design, rejecting linear models of progress. More recent contributions extend this dialogue: Hallström (2022) [10] argued that determinism manifests not only at macro-levels but also in micro-contexts such as design and education, while McLuhan (1964) [11] and Hauer (2017) [12] underscored how media and digital networks restructure perception and everyday life. Collectively, these works highlight the interplay between technical possibility and societal context in shaping technological outcomes.

Parallel to these debates, neo-institutional theory highlights the decisive role of institutional environments in structuring technological and organizational change. Meyer and Rowan (1977) [13] conceptualized organizational structures as myths conferring legitimacy, often decoupled from technical efficiency, while DiMaggio and Powell (1983) [14] categorized the isomorphic pressures—coercive, mimetic, and normative—that drive organizational homogeneity. Scott (2008) [15] consolidated this perspective into regulative, normative, and cultural-cognitive pillars, offering a comprehensive model of institutional influence. Applications in technology studies demonstrate the persistence of these dynamics: Currie (2011) [16] showed that regulatory and policy frameworks significantly affect IT adoption, Alexander (2012) [17] revealed how institutional contexts shape alliance innovation outcomes, and Roszkowska-Menkes (2023) [18] extended the framework to sustainability, showing how institutional pressures foster conformity to green practices. More recent scholarship emphasizes agency within institutions. Friedland and Alford (1991) [19] introduced institutional logics as meaning systems that both constrain and

enable actors, while Battilana et al. (2009) and Garud et al. (2013) [20,21] elaborated on institutional entrepreneurship as the process through which embedded actors mobilize coalitions to enact change. Meckling (2021) [22] further demonstrated how governments can act as institutional entrepreneurs, designing industrial policies to align demand-pull and technology-push measures for decarbonization.

Transition theory provides a complementary framework for analyzing systemic change in technology-intensive industries. Geels (2002) [23] articulated the multi-level perspective (MLP), in which niche innovations interact with regimes and landscapes to reconfigure socio-technical systems, a model extended by Geels and Schot (2007) into typologies of pathways including transformation, substitution, and reconfiguration [24]. Kemp et al. (1998) [25] operationalized these insights through Strategic Niche Management (SNM), demonstrating how protected spaces for experimentation generate learning and networks that catalyze regime shifts. Recent regulatory scholarship further highlights the temporal dimension of transitions: Ahern (2021) [26] examined regulatory lag as a barrier to innovation, while Ahern (2025) [27] advanced anticipatory governance, emphasizing foresight, policy experimentation, and sandboxes as mechanisms for adaptive regulation. Together, these studies show that successful transitions require alignment of technological niches, institutional structures, and governance timing.

Within the maritime sector, decarbonization literature illustrates the application of these theories in practice. Shan and Chircop (2020) [1] identified the IMO's Initial GHG Strategy as a test of institutional capacity, likely requiring structural reforms and market-based measures. Mallouppas and Yfantis (2021) [28] synthesized technological and operational measures alongside financial incentives, emphasizing that deep decarbonization necessitates joint advances in both policy and technology. Studies of adoption factors confirm the role of institutional and normative pressures: Sideri et al. (2021) [29] found that LNG and electrification uptake in Greece depends as much on social norms and risk perception as on technical efficiency. Harahap et al. (2023) [30] combined techno-economic modeling with socio-technical transitions to show that renewable fuels such as biomethanol and hydrogen become viable only beyond specific carbon price thresholds, while firm responses diverge between early adopters and resistant incumbents. At the global scale, Caprace et al. (2025) [31] demonstrated through integrated modeling that technical and operational measures alone can reduce emissions by up to 44%, but MBMs and policy design critically determine adoption portfolios and cost impacts. Regional studies, such as Chen and Cheng (2025) [32] on Arctic shipping, further highlight governance fragmentation and the importance of polycentric coordination. Complementary research underscores enabling conditions: Shi et al. (2023) [33] emphasized renewable fuel production pathways, Sun et al. (2023) [34] optimized hybrid ship energy management, and Qi and Wang (2023) [35] with Wang et al. (2022) [36] modeled LNG infrastructure deployment and subsidy design, while Peng et al. (2021) [37] systematized bunkering station planning and Han et al. (2019) [38] reviewed environmental compliance technologies.

Building on these insights, recent scholarships have examined how the IMO's carbon reduction initiatives, particularly the concept of Green Shipping Corridors, are accelerating technological advancement in zero-emission shipping. The Clydebank Declaration (2021) [39] and subsequent regional partnerships have positioned such corridors as experimental ecosystems where regulatory ambition, fuel innovation, and port infrastructure development converge. Studies and reports by the Global Maritime Forum (2024) [40] and IMO (2023) [3] indicate that corridors linking major trade routes—such as Singapore–Rotterdam (methanol), Japan–Australia (ammonia), and the Nordic hydrogen initiatives—function as policy-driven laboratories that connect industrial actors, governments, and classification societies. Technological progress in fuel-supply systems, digital

monitoring, lifecycle emission tracking, and digital-twin-based operational optimization has been particularly stimulated through these collaborative networks. Consequently, the Green Shipping Corridor framework exemplifies the alignment of global governance and technological innovation that underpins maritime decarbonization.

Previous studies therefore converge on the insight that maritime decarbonization is not a purely technological phenomenon but a policy-shaped and institutionally mediated transition. Nonetheless, significant gaps remain. Most research examines single cases, technologies, or policies in isolation, lacking cross-national comparative analysis of how policy design, institutional pressures, and techno-economic feasibility interact to drive adoption. Few studies explicitly integrate regulatory timing, anticipatory governance, and multi-level transition dynamics into empirical models. Moreover, the bidirectional relationship between policy and technology—where state interventions shape innovation trajectories while emergent technologies feed back into institutional logics—remains underexplored.

This study addresses these gaps by fusing insights from technological determinism, neo-institutionalism, and transition theory into a comparative framework. By analyzing the coupling between national maritime policies and technological development trajectories across countries, it contributes an original methodological approach that integrates institutional pressures, techno-economic thresholds, and governance timing. In doing so, it provides a novel perspective on how policy–technology interactions can accelerate eco-innovation pathways in shipping and shipbuilding while ensuring cost-effectiveness and long-term sustainability.

1.3. Research Objectives

This study aims to systematically examine how Japan, China, and Korea integrate technological innovation and institutional design to transform their shipping and shipbuilding industries toward eco-friendly vessels. This study developed a conceptual model to analyze technology–policy linkages in Japan, China, and Korea—three major East Asian countries that lead the global shipbuilding and maritime industries, encompassing both upstream shipping and downstream shipbuilding activities. The direction of linkage was examined through qualitative analysis of government policy documents, industry reports, and pilot project data. In this process, the sequence and causal relationships between technological innovation and policy development were reviewed to verify the accuracy of each linkage type. The verified causal patterns were then quantified within a comparative analytical framework to support cross-country comparison. Finally, the study presents conclusions that highlight observable implications for policy and industrial practice.

The temporal order and causal relationships underlying the following hypotheses were represented as observable visual data based on the comparative framework of this study, which included the dimensions of technological maturity, government policy, social reflection, and finance/infrastructure. The analysis yielded the following findings.

- As the alignment among the four axes increases, the frequency and continuity of the verification–standardization–diffusion–reinvestment cycle between technology and policy also increase, while the time lag between regulation and technology adoption in eco-friendly ship conversion decreases.
- When maritime verification and standardization activities for new technologies take precedence, institutional responsiveness to technological change increases, prompting revisions to standardized guidelines.
- The clearer the structure of policy instruments—such as catalogs, action plans, subsidies, and public procurement—the greater the potential for eco-friendly ship construction, retrofitting, and hinterland infrastructure development.

- The combination of public demonstration support and financial incentives through policy promotes a stepwise, bidirectional interaction between technology and policy, through which limited public initiatives expand into private markets.
- The absence of a diversified green-fuel infrastructure weakens the necessary conditions for implementing decarbonization strategies; conversely, the combination of financial support, standardization, and land–sea verification forms a sufficient condition for accelerating decarbonization implementation.

Ultimately, this study develops a circular logic model of policy–technology interaction. In this model, the alignment of four indicators determines the direction and strength of interaction; national pathways are classified as innovation-led convergence, institution-driven execution, or coordination-based cyclic models; and regulation functions as institutional infrastructure that initiates the process from demonstration to standardization and diffusion.

Through this framework, the study offers both an integrated academic model that bridges policy, technological innovation, and transition theory, and practical policy–industry roadmaps applicable to national strategies and corporate investments.

2. Theoretical Framework and Methodology

2.1. Theoretical Framework

2.1.1. Technological Determinism

Technological determinism views technological advancement as the primary driver of social change, functioning as a force that restructures political, economic, and social orders [10]. Karl Marx, through his analysis of modes of production, identified technology as the fundamental driver of social relations and transformation [8]. Innovations such as the steam engine, railways, and electricity improved industrial efficiency and reshaped political structures, urban space, and labor relations [41]. Similarly, Marshall McLuhan’s proposition that “the medium is the message” reflects the determinist view that technology does not merely mediate human activity but fundamentally transforms social relations and cognition [11].

Technological determinism gained wide attention in the early 20th century but was criticized in the latter half of the century and ultimately classified into two forms. Hard determinism holds that technology dictates the direction of social change with little room for institutional agency, whereas soft determinism regards technology as a major driver but one mediated by institutional and cultural contexts [9].

In the shipping and shipbuilding industry, the transition to eco-friendly ships illustrates this dynamic: hydrogen and ammonia-fueled engines and fuel-cell propulsion were applied to commercial vessels before institutional standards were established, pressuring the IMO, EU, and national governments to revise regulations [33]. Technology precedes institutions, with policy functioning as a dependent variable. Moreover, technological determinism explains the speed gap between technology and policy: while green technologies advance rapidly, policy requires consensus and legitimacy, resulting in regulatory lag [26,27]. The spread of LNG-, hydrogen-, and ammonia-powered ships demonstrates commercialization driven by technology, with policies following belatedly through regulatory recognition and support [29,30]. Therefore, in the context of decarbonization within the shipbuilding and marine sectors, technological determinism positions emerging technologies—such as air lubrication system (ALS) and wind-assisted propulsion—as leading forces, while policy frameworks, exemplified by the establishment of IMO regulations, serve to institutionalize these technological advancements.

2.1.2. Institutional Determinism

Institutional determinism emphasizes that technological development and industrial change are shaped primarily by institutional environments [16]. Rooted in new institutionalism, it argues that organizational behavior is guided by efficiency or market logic as well as by institutional norms, rules, and cultural frameworks [18].

Meyer and Rowan (1977) and DiMaggio and Powell (1983) explained that organizations conform to coercive, normative, and mimetic pressures to secure legitimacy [13,14]. Accordingly, technological choices are constrained by these institutional pressures, leading firms to adopt similar structures and strategies [42].

As summarized in Table 1, institutional theory comprises three pillars—regulative, normative, and cognitive-cultural—that explain the trajectory of technological adoption [17].

Table 1. Three Axis of Institutional Theory.

Elements of Theory	Regulative	Normative	Cognitive
Compliance-based	Expedience	Social Obligation	Taken for granted
Mechanism	Coercive	Normative	Mimetic
Logic	Instrumentality	Appropriateness	Orthodoxy
Characteristic	Rules, Laws, Sanctions	Certification, Accreditation	Prevalence, Isomorphism
Legal basis	Legally sanctioned	Morally governed	Culturally supported, conceptually correct

Source: Scott, W. R. (1995) [43]. *Institutions and Organizations*, Thousand Oaks, CA: Sage. Author re-edited.

In the shipping industry, Japan's Green Innovation Fund promoted hydrogen and ammonia technologies through regulatory and financial measures [28,44], while China's Green Technology Promotion Catalog designated LNG, SCR, and electric propulsion as strategic technologies, thereby accelerating their adoption [45].

Institutional logics further explain how socially constructed values and beliefs determine which technologies gain legitimacy. As illustrated in Figure 1, institutional determinism also accounts for the social context of technological choice through the concept of institutional logics [19,22]. For example, the IMO exerts normative pressure by framing decarbonization technologies as global standards, while member states interpret and implement these choices through their national industrial policies [46].

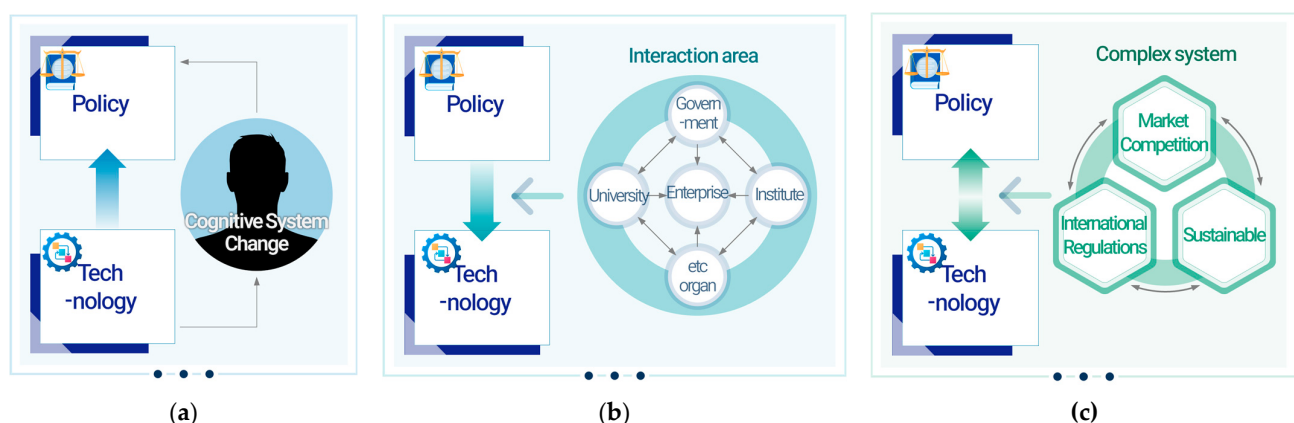


Figure 1. Comparison and Structure of Academic Theories: (a) Technological Determinism; (b) Institutional Determinism; (c) Technology–Institutional Circular Theory.

Recent institutional theory highlights the role of institutional entrepreneurs and institutional work in actively reshaping institutional environments [20,21]. In maritime decarbonization, governments, the IMO, classification societies, shipyards, and industry actors act as institutional entrepreneurs, legitimizing new green technologies or challenging existing institutional structures. The EU's FuelEU Maritime regulation exemplifies this dynamic, as multiple stakeholders institutionalize methanol, ammonia, and hydrogen as alternative fuels [47]. Universities and R&D institutes also contribute as institutional intermediaries, facilitating collaborative research and policy–industry linkages that reinforce these institutional changes [31].

Thus, institutional determinism explains maritime decarbonization not as the outcome of technology alone but as a process structured by institutional environments, pressures, and legitimacy-building mechanisms [48].

2.1.3. Perspective of Technology–Institution Cyclic Theory

This study integrates technological and institutional determinism to analyze the co-evolution of policies and technologies. Neither a unidirectional technology-driven nor institution-driven model fully explains the current maritime transition. Instead, eco-friendly innovation in shipping and shipbuilding demonstrates a cyclical interaction between technology and institutions [49].

Under the IMO 2050 net-zero goal, technological innovation generates new opportunities, while institutions legitimize, standardize, and diffuse selected technologies [23]. Technology exerts pressure on policy, and policy, in turn, reinforces commercialization and diffusion. This relationship is fluid and varies across time and context.

Since the 2020s, under the IMO-led reconfiguration of a new eco-friendly trade order, the shipping and shipbuilding industries have exhibited a high level of complexity, where environmental regulations, global market competition, and sustainability discourses are intricately intertwined [32]. As conceptualized in Figure 1, the technology–institution cycle highlights three key features—Technological Determinism, Institutional Determinism, Technology-Institutional Circular Theory.

2.2. Methodology

The design of this study begins with global environmental regulations on ship-induced air pollution, specifically the IMO 2030 carbon reduction target and the 2050 net-zero strategy and proceeds to analyze the interaction between national industrial policies and technological innovation in a stepwise manner. Accordingly, the study goes beyond simply listing cases or describing technological trends and instead focuses on clarifying the causal relationship between policy and technology. The research process maintains the systematic framework shown in Figure 2.

The analysis unfolds sequentially through four stages: Step-level qualitative mapping → Linkage direction classification → Quantitative scoring → Comparative visualization.

Each country's roadmap and policy initiatives were categorized into six developmental stages, ranging from initial innovation to institutional feedback. To illustrate the causal relationships and interaction flows, the linkage direction of each country was defined, and each stage was classified according to the direction of technological and policy influence, as presented in Table 2. In Table 2, the arrows along the driving axis for each country illustrate the direction of interaction between technology and policy.

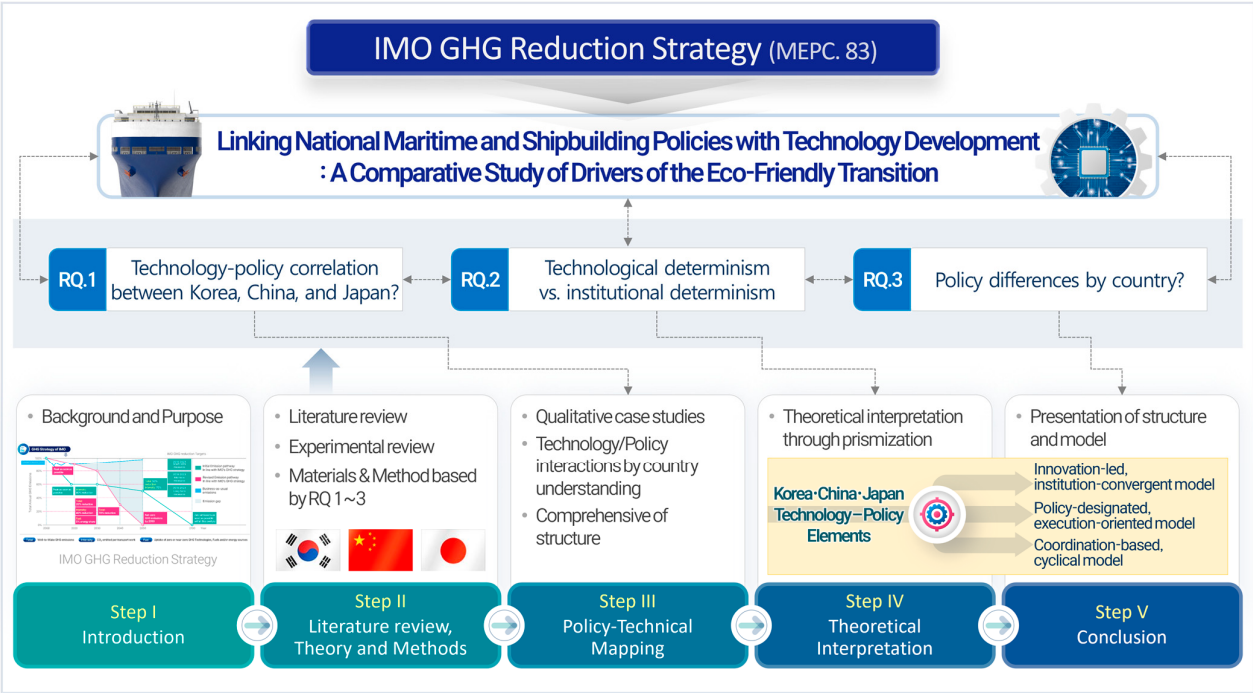


Figure 2. Research Framework of the Methodology.

Table 2. Technology-policy linkage analysis framework.

Category	Japan	Korea	China
Driving axis	Technology → Policy	Technology ↔ Policy	Policy → Technology
Steps 1–2	Demonstration, Industrial trends	Legal & institutional foundation, Policy	Policy designation, Target Setting
Steps 3–4	Standardization, Cluster	Financial support, Government cooperation	Financial support, Infrastructure
Steps 5–6	Institutionalization	Technology-Policy cycle	Institutional control and circular economy

Three directional types are defined based on initiation source, sequencing, dependency, and feedback evidence. Each linkage type was first categorized by its directional nature—technology-led, policy-driven, or feedback-based—before detailing the country-specific examples. The types of linkages were defined as presented in Table 3.

Table 3. Definition for Direction of Linkage Type.

Linkage Type	Causal Logi	Connectivity
Technology-led	Technology precedes and induces policy change.	R&D → Demonstration → Policy revision
Policy-driven	Policy initiatives trigger technological development or industrial adoption.	Regulation → Funding → Industrial response
Feedback-Based	Mature technology leads to new policy frameworks and reinvestment cycles.	Technology verification → Policy reinforcement → Reinvestment

Based on these interactions, four dimensions—technological maturity, regulatory readiness, social reflection, and infrastructure establishment—were quantified to produce comparative linkage scores. This scoring reflects how the linkage evolves from technological initiation to institutional feedback, thereby visualizing the co-evolution of technology and

policy across the three national contexts. The scoring structure is a normalized set of empirical data collected from official documents, records of technical demonstrations, and policy materials.

Each stage is both independent and interconnected within a coherent logical structure. Case studies on Japan, China, and Korea provide empirical foundations; policy–technology mapping links interactions among actors; and theoretical interpretation generalizes specific phenomena into academic frameworks. Finally, comparative analysis reveals differences and commonalities across countries, directly addressing the research questions by offering problem-solving insights. This stepwise design enhances academic validity by deepening results progressively rather than relying on linear enumeration.

3. Comparative Analysis of Policy–Technology Linkages in Northeast Asia

3.1. Japan

In 2020, Japan’s Ministry of Land, Infrastructure, Transport and Tourism (MLIT) announced a net-zero strategy to be achieved by 2050. In June 2021, they introduced the Green Growth Strategy toward Carbon Neutrality in 2050, providing a foundational plan for the sustainable development of the shipping and shipbuilding industries [50,51]. Through this process, Japan divided the maritime sector into non-power and power segments, outlined decarbonization measures for each, and designated 14 strategic priority fields for future growth [52]. This strategy demonstrates that Japan’s transition policy is closely aligned with the IMO’s 2030 reduction target and 2050 net-zero vision, ensuring an integrated and coherent relationship between policy and technology [53].

To support cluster-based growth in shipping and shipbuilding, the government established stepwise R&D roadmaps and financial support mechanisms, thereby linking eco-friendly policies with technological development, commercialization, and demonstration projects [44].

3.1.1. Policy Domain

The MLIT promotes the eco-friendly transition of the shipping and shipbuilding sector through four main approaches:

- Roadmap for fuel transition: By 2025, LNG and biofuels are expected to serve as transitional alternatives, with hydrogen- and ammonia-fueled ships targeted for commercialization after 2030 [54].
- Green Innovation (GI) Fund: Based on Article 16-3 of the NEDO Act (2002) [55], and under METI’s Basic Policy for the Green Innovation Fund, the GI Fund supports the development of hydrogen and ammonia engines, fuel supply systems, methane-slip reduction devices, and N₂O catalysts [56].
- Fuel infrastructure and standards: MLIT simultaneously develops roadmaps for infrastructure and institutional arrangements. LNG supply infrastructure is being expanded at major ports nationwide, while Japan has proposed safety guidelines for hydrogen and ammonia bunkering in anticipation of IMO standards [57].
- Finance and demand creation: MLIT fosters private-sector participation through demand-generation initiatives and financial incentives. For example, coastal shipping operators in the Imabari cluster receive financial support from the Japan Railway Construction, Transport and Technology Agency (JRRT) for ships equipped with energy-efficient technologies, along with technical consultation from JRRT experts [58].

Beyond MLIT, the Agency for Natural Resources and Energy subsidizes design, equipment, and verification costs in demonstration projects for coastal vessels using hydrogen and battery propulsion [59]. Additionally, the Ministry of the Environment, in cooperation

with MLIT, implements multi-ministry programs such as the Port Decarbonization Promotion Project, the Maritime Sector Decarbonization Promotion Project, and the Zero-Emission Ship Construction Promotion Project. These programs provide subsidies for equipment, retrofits, and renewable energy integration in hydrogen-, ammonia-, LNG-, methanol-, and electric-powered ships [60].

3.1.2. Technology Domain

Supported by government policies and institutional mechanisms, Japan's shipping and shipbuilding industries have advanced eco-friendly technologies, with private companies and regional clusters playing a key role.

- **Hydrogen and ammonia technologies:** Through the GI Fund and subsidies, companies such as Japan Engine Corporation (J-ENG) have developed the world's first low-speed hydrogen engine, while Yanmar developed a four-stroke dual-fuel medium-speed engine, in collaboration with Mitsui O.S.K. Lines (MOL) and Kawasaki Heavy Industries. The project aims for demonstration in 2027 and commercialization by 2030 [61,62]. Firms such as IHI, NYK Line, and ClassNK also participate in fuel supply systems and the development of safety guidelines, contributing to international standardization [63].
- **Biofuels:** Under the 7th Strategic Energy Plan (2025) [64], MLIT issued the Guidelines for Handling Biofuels in Ships [65], leading to joint demonstrations by energy companies (JX Nippon Oil & Gas, Idemitsu Kosan) and shipping companies (MOL, "K" Line, Shoen Kisen). For instance, MOL partnered with GoodFuels in the Netherlands to test biofuel blends in container and bulk carriers [66,67].
- **Battery and fuel-cell propulsion:** Private companies focus on small- and medium-sized passenger vessels. The e5 Project Consortium (Asahi Tanker, Exeno Yamamizu, MOL, Mitsubishi Corporation, etc.) developed the Hanaria ferry, equipped with hydrogen fuel cells, lithium-ion batteries, and biodiesel generators [62]. Oshima Shipbuilding has constructed battery-powered ferries [68]. In the large-vessel segment, NYK Line's CC-Ocean Project, in collaboration with Mitsubishi Shipbuilding and ClassNK, successfully captured CO₂ on board with 99.9% purity [69].
- **Maritime clusters:** The Imabari cluster, composed of Shoen Kisen, Imabari Shipbuilding, equipment suppliers, financial institutions, insurers, and port service firms, integrates construction, operation, finance, and logistics, creating a concentrated ecosystem [70,71]. This collaborative structure strengthens Japan's competitiveness in the eco-friendly transition.

In summary, Japan's case demonstrates a cyclical relationship: policies accelerate technological development through roadmaps, subsidies, infrastructure, and institutional arrangements, while technological demonstrations reinforce policy coherence and contribute to international standard-setting.

3.1.3. Policy–Technology Mapping

Japan's eco-friendly transition illustrates a structure of "innovation-led, institution-convergent" interaction. Technology-driven demonstrations are rapidly institutionalized through roadmaps, guidelines, subsidies, and financial incentives. Tables 4 and 5 illustrate this linkage.

Table 4. Japan’s Evaluation of the Policy–Technology Linkages in Shipping and Shipbuilding Industry.

Step	Technology Innovation	Policy/Institution	Linkage Type
[Step 1] Tech. Innovation ↔ Policy Reflection	- J-ENG hydrogen engine - MOL Biofuel demonstration - NYK CCUS	- MLIT Roadmap - Green Innovation Fund - Establishment of guidelines	Empirical results are directly reflected in policy (Top-down + Bottom-up)
[Step 2] Substantiation ↔ Infra. and Guideline	- e5 Project Hybrid Vessel - Oshima Shipbuilding Ferry	- Infrastructure for fuel - Biofuel guidelines - IMO guidelines	Technology verification → Infrastructure and guideline expansion (Bottom-up)
[Step 3] Technological ↔ Global Standard	- ClassNK, IHI, NYK R&D: Research for Fuel supply system and safety	- Government-initiated agenda - Revising domestic guidelines	Industry-led → Policy adoption & standardization
[Step 4] Cluster ↔ Institutional Support	- Imabari cluster—Shipbuilding, Owners, Equipment + Financing	- Joint support from the government and local governments, Institutionalization of collaborative platforms	Regional cluster ↔ institutional support (Network-driven linkage)
[Step 5] Private Innovation ↔ Financial Support	- Company for new shipbuilding, Tech. for energy efficiency	- JRTT Finance supporting Advisory by expert	Private innovation ↔ Financial support (Finance as linkage)
[Step 6] Additional Innovations ↔ Strengthening Policy Consistency	- Additional R&D after verification - Responsibility for market	- Reintroduction of subsidies, Policy revision and supplementation	A circular structure that continuously reinforces each other (Feedback loop)

Table 5. Japan’s Mapping-based 4-axis Connectivity Scale.

Axis	Key Step by Mapping	Connectivity
Technology maturity	Step 1, 2, 3, 5	4/6
Government’s regulation	Step 1, 3, 6	3/6
Social reflection	Step 3, 4, 6	3/6
Economic and institutional infrastructure	Step 2, 4, 5	3/6

3.2. China

China has pursued industrial development through a state-led strategy emphasizing self-reliance in core technologies, most notably via the Made in China 2025 plan [72]. In the shipbuilding sector, the government issued the Action Plan for Green Development of the Shipbuilding Industry (2024–2030), designating shipping and shipbuilding as strategic industries for green transformation, supported by large-scale state interventions [73]. This reflects strong institutional determinism, with the state accelerating commercialization by concentrating fiscal and institutional resources on designated technologies. Simultaneously, certain areas are directly shaped by international regulatory pressures, such as IMO conventions, indicating elements of technological determinism.

3.2.1. Policy Domain

China’s eco-friendly maritime and shipbuilding strategies are not fragmented among ministries but are implemented through inter-ministerial cooperation involving the Ministry of Industry and Information Technology (MIIT), the National Development and Reform Commission (NDRC), the Ministry of Finance (MOF), the Ministry of Ecology and Environment (MEE), and the Ministry of Transport (MOT) [70].

Green Industry Guidance Catalogue (2019 edition): Issued by the NDRC, this catalogue identified energy-saving, clean energy, and clean production technologies as priority

sectors, thereby institutionalizing financial and tax incentives for green technology development [74].

Green and Low-Carbon Transformation Industry Guidance Catalogue (2024 edition): Issued jointly by ten ministries, including NDRC, MIIT, and MEE, this catalogue extended the policy scope to the maritime domain, designating LNG propulsion, SCR aftertreatment, electric propulsion, and marine waste recycling as strategic green technologies [75].

Action Plan for Green Development of the Shipbuilding Industry (2024–2030): Jointly announced by five ministries, this plan set targets of achieving a 50% market share for LNG- and methanol-powered vessels by 2025 and establishing a globally leading eco-friendly technology system by 2030 [35].

Through these layered policies, China has institutionalized a state-led approach, positioning green shipping and shipbuilding as a strategic industry. By maintaining consistency with IMO frameworks such as EEXI, EEDI, and CII, while simultaneously implementing stricter domestic standards, China pursues a dual strategy: ensuring compliance with global regulations and establishing leadership in setting de facto standards.

3.2.2. Technology Domain

China's eco-friendly technologies are strongly shaped by state guidance:

- **LNG propulsion:** LNG has been strategically designated in both the 2019 and 2024 policy catalogs [76]. Hudong-Zhonghua Shipbuilding (CSSC) signed contracts with Qatar Energy to build eight Q-Max LNG carriers, demonstrating China's capacity to translate LNG R&D into global market competitiveness [36].
- **LNG bunkering infrastructure:** Recognized as essential for commercialization, the deployment of bunkering stations was optimized using empirical data such as shipping routes, fuel prices, and construction costs. COSCO analyzed its container routes to identify strategic bunkering hubs, including Shanghai, Shenzhen, and Ningbo, supported by subsidies [37,38]. Studies also quantified the effects of subsidies and construction efficiency on LNG ship commercialization [77]. Consequently, the commercialization of China's LNG bunkering technology goes beyond mere infrastructure expansion, strategically institutionalizing the close interaction between policy support (subsidies), technological development (dual-fuel engines), and infrastructure construction (port networks) [78]. By quantitatively assessing the effects of subsidy policies and construction costs in the shipping and shipbuilding sector, the Chinese government has established a cascade-type process in which policy and infrastructure are organically linked to vessel operation.
- **Ammonia propulsion technology:** Although still at an early stage, there are examples of shipbuilding technologies being extended to demonstration at the operational level. In December 2024, COSCO Shipping Heavy Industry built China's first ammonia/diesel dual-fuel tug, Yuan Tuo Yi (Yuantuo 1), which obtained AiP (Approval in Principle) from the China Classification Society (CCS) and ABS, and conducted truck-to-ship ammonia bunkering trials at the Dalian Shipyard. This prototype vessel is equipped with two Type-C ammonia storage tanks and dual-fuel engines, representing an important milestone in transitioning ammonia propulsion from the shipbuilding stage to operational deployment.
- **Electric and hybrid propulsion vessels:** China's electric and hybrid propulsion vessels remain at the demonstration stage in inland passenger and cargo shipping, with only limited early operation in some regions. According to the International Council on Clean Transportation (ICCT), China's electric and hydrogen fuel-cell ships are primarily being demonstrated mainly in inland passenger and short-haul cargo sectors [79]. As of 2025, the Green Transport Development Plan (2019–2022) and follow-up policies

of the Ministry of Transport (MOT) have institutionally enabled such demonstrations, providing a foundation for eventual commercialization.

- **Waste-to-resource and energy recovery technologies:** These technologies are closely linked to China's circular economy strategy and are being introduced mainly in port operations and shipbuilding [79]. Pilot projects have been launched at some Chinese ports to convert operational waste into fuel. These initiatives are institutionally supported by the Circular Economy Promotion Law of the People's Republic of China and resource circulation policies led by the NDRC [79].

Specifically, Shanghai Port has established reception facilities for ship wastewater, while Tianjin Port has implemented a system in which designated contractors collect and process all oily waste generated by vessels. Although carbon capture and CCUS (Carbon Capture, Utilization, and Storage) technologies remain at an early stage, experimental projects have demonstrated their feasibility: China Merchants Energy Shipping (CMES) and the China State Shipbuilding Corporation (CSSC) installed onboard carbon capture devices on large bulk carriers and tankers [80]. These technological developments and demonstrations are not merely responses to IMO's EEXI and CII regulations, but also represent strategic potential to enhance China's export competitiveness in the shipping and shipbuilding sectors.

Taken together, these cases clearly demonstrate that China's technological progress in shipping and shipbuilding is shaped by institutional determinism: national policies designate strategic technologies, set priorities and timelines, and firms pursue rapid commercialization within this framework. Together, certain technologies—such as LNG, SCR, and electric propulsion—have influenced policy in advance through international regulatory requirements (IMO NO_x and GHG rules), creating a dual mechanism in which institutions and technologies complement each other.

3.2.3. Policy–Technology Mapping

As shown in Tables 6 and 7, China's eco-friendly transition strategy in shipping and shipbuilding is strongly shaped by state-led institutional determinism. The government directly designates technology priorities through instruments such as the Green Industry Guidance Catalogue and the Action Plan for Green Development of the Shipbuilding Industry, and implements fiscal subsidies, tax incentives, and infrastructure expansion to promote a comprehensive green transition across the sector. This system functions not as a technology facilitator but an integrated industrial policy that organically combines national strategy, corporate demonstration, and international regulatory compliance—while simultaneously enhancing China's influence in shaping global norms.

Table 6. China's Evaluation of the Policy–Technology Linkages in Shipping and Shipbuilding Industry.

Step	Technology Innovation	Policy/Institution	Linkage Type
[Step 1] Specify strategy ↔ Inducing technological development	- [Green Industry Guidance Catalogue] - [Low-carbon Green Transformation Industry Guidance Catalogue] - LNG, SCR, electric propulsion, and waste recycling designation	- Hudong-Zhonghua LNG carrier project - Development of SCR post-treatment system - Technology for port waste treatment and resource recycling	Top-down Designation

Table 6. Cont.

Step	Technology Innovation	Policy/Institution	Linkage Type
[Step 2] Industry action plan ↔ Demonstration	- [Action Program for Green Development of Shipbuilding Industry ('24–'30)]: The goal is to achieve a 50% market share for LNG and methanol vessels by 2025 and to reach internationally leading levels by 2030	- Research of bunkering optimization-COSCO LNG, Demonstration for ammonia dual-fuel tugboat-Yuan Tuo Yi	Goal-driven Execution
[Step 3] Multi-departmental cooperation ↔ Focus on state-owned enterprises	- MIIT·NDRC·MOF·MEE·MOT etc. five ministries joint commitment	- COSCO, CSSC, etc. Large-scale shipbuilding and technology demonstration centered on state-owned enterprises	State-led Enforcement
[Step 4] Supporting finance/infrastructure ↔ Technology commercialization	- Subsidies, tax benefits, financial incentives, and expansion of LNG bunkering infrastructure.	- Study on the establishment of LNG bunkering hubs and optimal locations for the ports of Shanghai, Shenzhen, and Ningbo.	Policy-induced Commercialization
[Step 5] Responsibility of international regulatory ↔ Technology demonstration	- Ensuring consistency with IMO regulations (EEXI, EEDI, CII, MAR-POL) and applying strengthened domestic emission standards	- Electric-propelled and hybrid passenger ships are being operated, and CCUS-equipped vessels are being tested.	Dual Pressure Linkage
[Step 6] Circular economy policy ↔ Waste recycling	- [Circular Economy Promotion Law], a resource circulation policy centered on the NDRC	- Demonstration of port wastewater treatment facilities, waste fuel conversion, and energy recovery	Policy-driven Pilot

Table 7. China's Mapping-based 4-axis Connectivity Scale.

Axis	Key Step by Mapping	Connectivity
Technology maturity	Step 1, 2, 5, 6	4/6
Government's regulation	Step 1, 2, 3, 5, 6	5/6
Social reflection	Step 3, 5	2/6
Economic and institutional infrastructure	Step 2, 4, 6	3/6

3.3. Korea

In December 2020, the Korean government announced the First Basic Plan for the Promotion of Eco-Friendly Ships (2021–2030) under the Eco-Friendly Ship Act. The plan was designed to comply with IMO environmental regulations and domestic GHG reduction targets, positioning public ships as the primary vehicle for initiating the eco-friendly transition [81]. Accordingly, the government presented a ten-year roadmap (2021–2030) with the vision of “Greenship-K 2050,” aiming to reduce GHG emissions from domestic shipping by 70% by 2030 compared to 2017 and to achieve carbon neutrality by 2050 [82]. The plan consists of four main strategies: (1) eco-friendly transition of public ships, (2) formation of an industrial ecosystem for eco-friendly ships, (3) R&D and infrastructure development for eco-friendly ships, and (4) institutional foundations for transition.

3.3.1. Policy Domain

The Korean government has designated public ships as “first movers” to create demand for eco-friendly ship technologies [83]. Under Article 10 of the Eco-Friendly Ship Act, central and local governments and public institutions are mandated to build or retrofit eco-friendly vessels when ordering new ships [84]. The government provides subsidies

covering up to 50% of additional construction costs for public vessels, with KRW 2.5 trillion allocated to support 528 ships by 2030 [85].

During the implementation of consistent eco-friendly policies for the shipping and shipbuilding industries, supply measures were integrated with financial support schemes. Under the First Basic Plan for the Development and Supply of Eco-Friendly Ships (2021–2030), the Ministry of Oceans and Fisheries (MOF) prepares and enforces annual supply plans. Between 2021 and 2024, a total of 199 vessels—118 public and 81 private—were either newly built or retrofitted as eco-friendly ships [86]. In 2025, under the Implementation Plan for the Supply of Eco-Friendly Ships, Korea plans to support a total of 81 vessels—54 new buildings and 27 retrofits. In the public sector, this includes constructing 34 eco-friendly vessels (electric propulsion, hybrid, etc.) and installing particulate matter reduction devices (DPFs) on 15 existing ships. In the private sector, 20 eco-friendly fuel-powered vessels will be built, while 12 vessels will receive support through financial mechanisms such as interest subsidies. To further encourage participation from small coastal shipping companies, the Ministry of Oceans and Fisheries (MOF) launched the 2025 First Eco-Friendly Certified Ship Supply Support Program (31 January–27 March 2025), offering subsidies of up to 30%, depending on certification grade and construction cost [87].

Korea has also focused on building technological and infrastructural foundations. LNG bunkering infrastructure has been expanded in major ports such as Busan, Gwangyang, and Ulsan, alongside the development of supply chains for alternative fuels including green methanol and green ammonia [88]. Korea also plans to establish a trans-Pacific zero-carbon Green Shipping Corridor between the United States and Busan by 2027 as a strategic initiative for international cooperation [89]. Furthermore, the government has introduced multi-layered financial packages including policy finance, green finance (K-Taxonomy), tax incentives, and shipbuilding fund support. The Korea Marine Safety Authority (KOMSA) operates an eco-friendly ship certification system, which institutionalizes phased support for LNG-, methanol-, ammonia-, hydrogen-fueled, and battery-powered vessels. This institutional framework goes beyond passive compliance with IMO regulations by linking to international standardization activities such as ISO and IEC, thereby ensuring that domestically developed technologies are compatible with global norms [90].

Consequently, Korea's eco-friendly shipping and shipbuilding policy began with the adoption of the IMO 2050 net-zero strategy, advanced through domestic legislation and the establishment of basic plans, and has since expanded to include supply measures and financial support for effective policy implementation. With infrastructure development and international cooperation centered on demonstration projects, Korea has progressed to the stage of shaping global standards.

This multi-layered and chronological framework has internalized IMO regulations as a national strategy. Ultimately, it serves as a core mechanism that drives the competitiveness of Korea's shipping and shipbuilding industries while steering the decarbonization paradigm through eco-friendly ship technology development, early commercialization, and active participation in international standardization.

3.3.2. Technology Domain

At the national level, technology development has been driven primarily by the Ministry of Trade, Industry and Energy (MOTIE) and the Ministry of Oceans and Fisheries (MOF). The Korean government has identified the development of low- and zero-carbon propulsion systems and the localization of eco-friendly equipment as key priorities. Core technologies under development include LNG-, methanol-, ammonia-, and hydrogen-fueled engines and fuel supply systems, large-scale fuel cells, and direct current-based electric propulsion systems. In parallel, efficiency-enhancing equipment such as waste heat

recovery systems, air lubrication systems, and wind-assist devices (rotor sails and wing sails) is also being developed [91].

First, the MOF is implementing the Core Technology Development Project for Eco-Friendly Ships (2022–2031; KRW 260 billion) and has initiated construction of the Hybrid Propulsion Land Demonstration Center in Yangsan, Gyeongsangnam-do. This center evaluates and demonstrates electric and hybrid propulsion systems for mid- to large-sized ships, while also serving as a key facility for promoting the localization of equipment that is still heavily dependent on imports [92]. The Korea Marine Equipment Research Institute (KOMERI) has also established a Multipurpose Offshore Testbed, which enables equipment verified onshore to be tested under real operating conditions [90].

Second, the Korean Register (KR) and HD Hyundai Heavy Industries successfully recovered boil-off gas (BOG) generated during the construction of LNG carriers and converted it into city gas in 2025, marking the world's first decarbonization achievement at the shipyard construction stage [93]. Samsung Heavy Industries (SHI) has also installed amine-based onboard carbon capture and storage (CCUS) systems on HMM's 2200 TEU containerships since 2024, with performance verified monthly—representing Korea's first maritime demonstration of onboard carbon capture.

Third, Hyundai Merchant Marine (HMM), as part of its ESG management strategy, has ordered and begun operating LNG/methanol dual-fuel ultra-large containerships [94]. Between 2023 and 2024, HMM secured a fleet of 12 dual-fuel containerships, and in 2025 initiated demonstration voyages equipped with wing sails and carbon capture units (CCUs), illustrating how private shipping companies are advancing eco-friendly technology commercialization through ESG-based strategies.

Fourth, the Korean Agency for Technology and Standards (KATS) released the High-Value Future Ship Standardization Roadmap (2024), which sets targets of 30 international proposals and 47 domestic standards by 2028 [95]. The roadmap covers standards for ammonia fuel system safety, methanol fuel supply, and hybrid electric propulsion interfaces, which Korea intends to propose to ISO and IEC. This strategy underscores Korea's ambition to secure a leading role in global rulemaking.

Overall, Korea has established a virtuous cycle of policy–technology–industry diffusion by integrating government-led financial support and policy facilitation, land- and sea-based demonstration infrastructure, decarbonization verification at the shipyard stage, private-sector ESG adoption, and international standardization initiatives. This approach reflects both the IMO's technology-neutral regulatory philosophy and Korea's institutional determinism in selecting and prioritizing specific eco-friendly technologies.

3.3.3. Policy–Technology Mapping

As shown in Tables 8 and 9, Korea's eco-friendly shipping and shipbuilding policy links policy and technology through a phased framework: legal and institutional foundation → technology development and demonstration → industrial diffusion and standardization. This process extends beyond legislation and planning by combining mandatory public-sector conversion with private-sector incentives to promote tangible commercialization and broader diffusion.

Simultaneously, Korea has responded to IMO environmental regulations (EEXI, CII, MARPOL Annex VI) while introducing complementary policy tools, such as K-Taxonomy-based green finance, tax incentives, and public procurement, thereby creating a virtuous cycle of technology development, demonstration, and diffusion. As the evaluation results, Korea is rapidly achieving technological maturity and economic feasibility for LNG, methanol, ammonia, hydrogen propulsion, and emerging electric/fuel-cell technologies through phased demonstrations. In parallel, Korea is enhancing institutional predictabil-

ity through its 2050 Carbon Neutral Roadmap and expanding social and environmental acceptance through early public-sector transition.

Table 8. Korea’s Evaluation of the Policy–Technology Linkages in Shipping and Shipbuilding Industry.

Step	Technology Innovation	Policy/Institution	Linkage Type
[Step 1] Establishing a legal and institutional foundation ↔ Inducing technological development	- [Act on Promotion of Development and Distribution of Environmentally Friendly Ships]	- Development of LNG, methanol, ammonia, and hydrogen engines, and research into direct current-based electric propulsion systems.	Legal–Institutional Induction
[Step 2] Establishment of basic plan ↔ Expansion of demonstration	- [The First Basic Plan for the Development and Distribution of Eco-Friendly Ships (2021–2030)]	- The goal is to convert 388 public and 140 private vessels, demonstrating pilot projects through public procurement	Target-driven Demonstration
[Step 3] Multi-departmental cooperation ↔ Focus on state-owned enterprises	- MOTIE·MOF partnership [International Shipping Decarbonization Strategy]	- Expansion of LNG and methanol infrastructure in Busan, Ulsan, and Gwangyang ports, piloting international green shipping routes.	Multi-ministerial Coordination
[Step 4] Financial support ↔ Technology commercialization	- Subsidy (Max. 30%), Acquisition tax reduction, Green finance (K-Taxonomy)	- HMM-Demonstrations of LNG Methanol dual-fuel vessel orders and operations, wing sail and CCU	Financial–Commercial Linkage
[Step 5] Contribution to international regulations ↔ Technology demonstration	- IMO Regulatory(EEXI, CII, MARPOL convention) Ensuring consistency	- KR·HD KSOE-LNG BOG recycling demonstration, SHI-Demonstration of onboard CCUS	Regulation-driven Verification
[Step 6] Circular economy policy ↔ Reinvestment and expansion	- [2023 Implementation Plan for the Distribution of Eco-Friendly Ships], KATS [High-Value-Added Future Ship Standardization Roadmap]	- Aiming for 30 international standardization proposals (ISO/IEC), research and demonstration of domestic production of equipment	Circular Policy–Standardization Feedback

Table 9. Korea’s Mapping-based 4-axis Connectivity Scale.

Axis	Key Step by Mapping	Connectivity
Technology maturity	Step 1, 2, 5, 6	4/6
Government’s regulation	Step 1, 2, 3, 5, 6	5/6
Social reflection	Step 2, 3, 6	3/6
Economic and institutional infrastructure	Step 3, 4, 6	3/6

4. Comparative Analysis of Policies and Technologies in Korea, China, and Japan

4.1. Comparison of Policy and Technology Approaches

Korea, China, and Japan have all identified the eco-friendly transition of shipping and shipbuilding as a national strategic priority within the framework of international regulations, particularly the IMO’s 2030 GHG reduction target and 2050 net-zero strategy. As shown in Table 10, the three countries share several key characteristics: all are IMO Council members with direct influence on rulemaking; all possess world-class shipbuilding capabilities; and all operate large-scale global fleets. These shared foundations underpin intensified competition to achieve technological leadership in the eco-friendly transformation of shipping and shipbuilding.

Table 10. Multi-Level Comparison of Policies and Technological Development in Korea, China, and Japan.

Division	Japan	China	Korea
Policy and Strategy	- Goal-based and technology-neutral regulation - Large-scale financial support through ‘Green Innovation Fund’ - Preemptive establishment of bunkering guidelines for LNG, ammonia and hydrogen - Simultaneous financial and demand creation, including JRIT etc.	- Technology designation through [Green Technology Promotion Catalog] - Large-scale investments and subsidies centered on state-owned enterprises - Early Expansion of LNG and Methanol Infrastructure: A Dual Strategy of International Standards and Strengthened Domestic Regulations	- [Eco-Friendly Ship Law (Ministry of Oceans and Fisheries & Ministry of Trade, Industry and Resources, 2018)] [96] - Mandatory conversion of public vessels and initial demand creation through public procurement - Providing a package of policy financing, green financing, and tax support - Phased expansion of bunkering infrastructure.
Technology Strategy	- Hydrogen/ammonia engine demonstration (2026~) and commercialization (2030~) - Development of methane slip and N₂O reduction catalyst technology - Expanding the use of fuel cells, batteries, and hybrids - Demonstration of air lubrication, wind power assistance, and onboard CCUS	- Deployment of LNG-powered vessels is increasing, leading to increased international orders. - Commercialization of SCR post-treatment technology - Introduction of electric propulsion and hybrid technology for coastal passenger ships - Commercialization of ammonia and hydrogen technologies is targeted for after 2030 - Waste recycling and CCUS pilot demonstrations are underway	- Development of LNG, methanol, ammonia, and hydrogen engines - Domestic production of fuel cells, electric propulsion, and equipment - Development of energy-efficient devices such as air lubrication and wind power assistance - Demonstration of a CCUS-applied pilot ship and NO_x and SO_x reduction devices - Construction of a pilot ship and establishment of a test bed through the “Green Ship-K Project”
Industrial Ecosystem	- Accelerate the establishment of standardization and certification infrastructure across shipyards, equipment, and classification societies. - Leading international standardization efforts.	- Vertical integration centered on state-owned enterprises - Simultaneous expansion of ports and fuel networks, achieving economies of scale	- Encouraging private sector expansion through public vessel demonstrations - Domestic production of equipment and phased construction of port infrastructure - Active participation in international standardization activities
Theoretical basis	- Technological determinism - Technological verification puts pressure on institutions, and institutions reinforce technological diffusion	- Institutional determinism: Institutions dictate and accelerate technological paths. - Technological deterministic pressures coexist in some fields.	- Technology-Institutional Circlic Theory: Simultaneous design of public policy and technology verification, a mutually complementary circular structure.

However, the specific approaches to integrating policies and technologies differ across countries. Japan follows a mutually reinforcing cycle of technological demonstration and institutional adjustment, pursuing a gradual and systematic transition through public–private collaboration. China adopts a speed-oriented model, in which the state designates strategic technologies, channels resources through subsidies and industrial policies and accelerates commercialization within short timeframes. In contrast, Korea emphasizes

a coordination-based and inclusive model that combines public procurement, policy finance, tax incentives, and phased infrastructure expansion to encourage broad industry participation, thereby balancing policy, technology, and industrial diffusion.

First, Japan bases its approach on goal-oriented and technology-neutral regulation, while fostering innovation through adaptive regulatory mechanisms, such as sandbox schemes, alternative design approvals, and periodic reviews. These policies are closely connected to demonstration projects: research on bottleneck technologies—hydrogen- and ammonia-fueled ships, methane slip reduction, and N₂O mitigation—illustrates a cyclical reinforcement in which technological advancements drive institutional adaptation, and institutions, in turn, facilitate technology diffusion. This virtuous cycle aligns with Japan's strategic objective of positioning itself as a leader in international standardization.

Second, China demonstrates a strong institutional-determinist approach. Through the Green Technology Promotion Catalog, it strategically designates LNG, SCR aftertreatment, electric propulsion, and waste-to-resource technologies, channeling substantial subsidies and financial incentives toward them. Simultaneously, China expands port and bunkering infrastructure while enforcing domestic regulations that are stricter than international standards, thereby driving rapid industrial transformation. Within this framework, institutional choices determine the pace of technology diffusion. Nevertheless, for certain technologies such as LNG, SCR, and electric propulsion, international regulatory pressure and global market demand have influenced policy formulation, indicating the coexistence of elements of technological determinism.

Third, Korea adopts a coordination-based and cyclical strategy positioned between the models of Japan and China. Following the enactment of the Eco-Friendly Ship Act and the establishment of basic plans, Korea mandated the eco-friendly conversion of public vessels, generating initial demand through public procurement. In parallel, policy finance and tax incentives reduce the burden on private firms, while LNG, methanol, ammonia, and hydrogen bunkering infrastructure is gradually expanded. Korea also actively engages in international standardization initiatives. On the technological front, projects such as Greenship-K involve constructing demonstration vessels and expanding sea trials to accelerate commercialization. Through these efforts, Korea supports the achievement of carbon reduction targets via new-fuel propulsion systems, CCUS, and energy-efficiency equipment development. This approach exemplifies the technology–institution cyclic model, in which public vessels serve as testbeds to build reliability and subsequently diffuse technologies to the private sector.

4.2. Analysis of Results and Academic Implications

Derivation of Research Findings and Implications

The findings of this study indicate that while Japan, China, and Korea all respond to international regulatory pressures—the IMO 2030 GHG reduction target and the 2050 net-zero strategy—they adopt distinct approaches to linking policy and technology.

Japan follows an innovation-led, institution-convergent model. In key areas such as hydrogen- and ammonia-fueled ships, fuel cells, and methane slip and N₂O reduction devices, Japan collects demonstration data at an early stage. These data are subsequently used to revise classification society rules and safety guidelines. The outcomes of the demonstration projects are directly incorporated into international standardization discussions, and institutions institutionalize these diffusion pathways. As illustrated in Figure 3, Japan's case demonstrates a cyclical mechanism in which technological demonstrations influence institutions, and institutions, in turn, reinforce technology diffusion. This represents a virtuous cycle that combines technological determinism with institutional alignment.

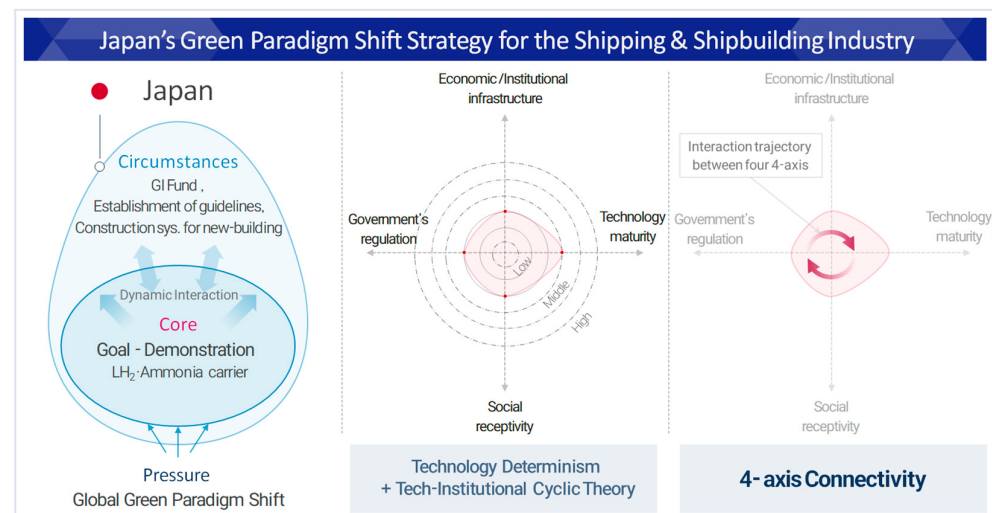


Figure 3. Japan's Innovation-Led, Institution-Convergent Model for Eco-Friendly Shipping and Shipbuilding by Paradigm Shift.

In contrast, China demonstrates a policy-designated, execution-oriented model. Through the Green Technology Promotion Catalog, the government identifies LNG, SCR aftertreatment, electric propulsion, and waste-to-resource technologies as “strategic technologies,” concentrating subsidies and infrastructure investments primarily through state-owned enterprises. As shown in Figure 4, policy directly determines the technological pathway, enabling rapid commercialization and diffusion. This represents a strong example of institutional determinism. However, in areas such as LNG, SCR, and electric propulsion—where international regulations and global market demand are significant—technological pressures can sometimes precede and shape policy formulation. Thus, China's model combines a dominant institution-driven designation–execution structure with partial elements of technological determinism.



Figure 4. China's Policy-Designated, Execution-Oriented Model for Eco-Friendly Shipping and Shipbuilding by Paradigm Shift.

Korea adopts a coordination-based, cyclical model positioned between the approaches of Japan and China. Following the enactment of the Eco-Friendly Ship Act and the mandate for public-sector vessel conversion, Korea generated initial demand through public procurement and policy finance. Simultaneously, through demonstration projects such

as Greenship-K, technologies are gradually validated and subsequently linked to private-sector diffusion. As shown in Figure 5, Korea's model illustrates a cyclical structure in which the interaction between policy and technology shifts flexibly across phases, minimizing transition costs. This framework aligns closely with the technology–institution cyclic theory, particularly by using public vessels as testbeds for industrial learning.



Figure 5. Korea's Coordination-Based, Cyclic Model for Eco-Friendly Shipping and Shipbuilding by Paradigm Shift.

In summary, the most significant finding from the Korea–China–Japan comparison is that the relationship between policy and technology is conditional rather than fixed. Specifically, depending on the degree of alignment across four dimensions—technological maturity (TRL), economic feasibility and infrastructure (TCO, fuel and bunkering systems), institutional predictability (regulatory coherence, approval procedures), and socio-environmental acceptance (GHG and community impacts)—technology may drive institutional adaptation (as in Japan), or policy may designate and enforce specific technological pathways (as in China). Korea, in contrast, balances these four dimensions across phases to mitigate transition risks.

Accordingly, this study empirically confirms that in the decarbonization transition of shipping and shipbuilding, policy–technology interactions are contextual and nonlinear, with the degree of alignment across the four dimensions determining the intensity and direction of the cycle.

4.3. Study Implications

Under the common pressure of the IMO 2030 GHG reduction target and the 2050 net-zero strategy, this study analyzed the policy–technology linkage structures of Japan, China, and Korea through a four-step process: qualitative stage mapping, linkage direction classification, quantitative scoring, and comparative visualization. Each country's linkage direction and case evidence were examined within a comparative framework comprising four dimensions—technological maturity, government policy, policy reflection, and finance/infrastructure. From this analysis, three propositions were derived for the eco-friendly transition paradigm:

- Proposition A (Technology → Policy transition): When verification capacity for eco-friendly ship technologies is high, institutional change follows technological validation with minimal delay, as seen in Japan's innovation-led institutional convergence model.

- Proposition B (Policy → Technology transition): When policy designation is explicit and enforcement is strong, technology development begins rapidly, reflecting China's policy-driven execution model.
- Proposition C (Balance → Enhanced Circulation): The greater the balance among the four dimensions, the more active and continuous the circulation between technology and policy becomes; however, such balance does not necessarily accelerate the overall pace of technological or policy advancement.

To derive the propositions, three theoretical foundations—technological determinism, social determinism, and the technology–institutional circulation theory—were applied as interpretive frameworks for determining the direction of linkage. By integrating these theories with qualitative case analyses, this study confirmed that theoretical directionality can serve as a driving mechanism in the interaction between technology and policy. However, during the analysis, it was observed that while certain causal linkages exhibited traction, the balance and acceleration between technology and policy linkages remained limited.

This analysis provides direct implications for Korea's policy design and industrial strategy. The Ministry of Oceans and Fisheries (MOF) should strengthen its platform function beyond compliance with IMO regulations by integrating public policy with technological demonstration. A key role of the platform is to accumulate and apply eco-friendly maritime data based on actual ship operations. Maritime data provides an empirical basis for formulating detailed safety guidelines and procedures. Furthermore, maritime data functions as a strategic lever for Korea to strengthen its leadership in international standardization activities, including those led by the IMO, ISO, and IEC.

Based on this study, a mid- to long-term (2025–2050) roadmap for GHG reduction in Korea's shipping and shipbuilding sectors has been established, as shown in Table 11. In addition, the outcomes of this research served as the foundation for formulating the roadmap presented below.

Table 11. Korea's the Mid- to Long-Term Carbon-Neutral Roadmap for Shipping and Shipbuilding to shift the Paradigm ('25~'50).

Step (Period)	Policy/Rules	Technology/Demonstration	Finance and Markets	International Leadership
Step 1 ('25~'30)	Main objectives: Strengthening the institutional foundation and expanding initial demonstrations			
	① Revising [Eco-Friendly Ship Law] including enforcement decree ② Institutionalization for K-Transition Finance	① Demonstration of LNG, methanol, electricity, and fuel cells on public vessels ② Data standardization linked to KOMSA certification	① Providing a package of policy financing, subsidies, and tax reductions ② Establishing a public–private risk-sharing structure	① Reflecting empirical data in ISO/IEC and IMO ② Expanding participation in international working groups
Step 2 ('30~'40)	Main objectives: Leading industrial expansion and international standards			
	① Extension and supplementation of the first basic plan ② Establishing a framework to promote the transition to private sector leadership	① Expanding the supply of eco-friendly ships in the private sector ② Focused development of technologies such as ammonia engines and hydrogen fuel cells	① Support for the localization of eco-friendly equipment ② Eco-friendly fuel support based on land–sea linkage verification	① Leading ISO/IEC ship and equipment standards ② International expansion of K-Greenship Certification linked to the Green Corridor
Step 3 ('40~'50)	Main objectives: Completing a carbon-neutral shipping system and establishing global leadership.			

First, technology and policy are interpreted as sequential and interactive processes, where the degree of alignment among the four axes—technological maturity, government

policy, policy reflection, and finance/infrastructure—determines the intensity of their cyclical linkage.

Second, Korea's transition toward eco-friendly shipping and shipbuilding follows a coordination–circulation model; although balanced, the pace of technological and institutional advancement remains limited.

Finally, Korea continues to pursue cost-efficient compliance with IMO decarbonization regulations while maintaining competitiveness among Northeast Asian countries. To realize a virtuous cycle between technology and policy, Korea must reinforce its integrated shipping–shipbuilding platform to promote balanced and accelerated co-evolution of both domains.

5. Conclusions

This study systematically compared and analyzed the policy–technology linkages of Japan, China, and Korea within the global regulatory framework of the IMO 2030 GHG reduction target and the 2050 net-zero strategy. Employing a four-stage design—qualitative case studies, policy–technology mapping, theoretical interpretation, and comparative analysis—it provided a structured framework to trace interactions between policy and technology beyond fragmented approaches.

The results indicate that while all three countries respond to common international regulatory pressures, they follow distinct models of policy–technology linkage. Japan adopts an innovation-led, institution-convergent model, in which technological demonstrations influence institutions, and institutions, in turn, reinforce diffusion. China follows a policy-designated, execution-oriented model, where institutional choices determine technological pathways and accelerate commercialization. Korea pursues a coordination-based, cyclical model that balances public demonstrations and policy finance to minimize transition costs. These findings confirm that the sequencing of policy and technology is context-dependent, shaped by the alignment of technological maturity, economic feasibility and infrastructure, institutional predictability, and socio-environmental acceptance.

The academic contributions of this study are fourfold: it (1) proposes a cyclic co-evolutionary perspective that moves beyond the traditional dichotomy of technological and institutional determinism; (2) identifies points where policy drives technology and where technology influences policy, bridging the fields of policy studies and innovation research; (3) reconceptualizes regulation as enabling institutional infrastructure that facilitates demonstration, standardization, and diffusion; (4) generalizes the strategic implications of Japan's, China's, and Korea's models for global standard-setting and industrial competitiveness.

The study acknowledges limitations in data availability for early-stage technologies (e.g., ammonia, hydrogen, onboard CCUS), the challenge of policy–technology endogeneity, and the impact of exogenous factors such as fuel price volatility and geopolitical shocks. Future research should complement this analysis with quantitative modeling approaches (e.g., system dynamics, agent-based models) and expert focus group interviews (FGIs) to address these gaps.

From an industrial perspective, the study highlights several positive implications: (1) coordinated collaboration around public demonstrations, the cost of transition to eco-friendly ships, international standardization, and bottleneck technology resolution can systematically reduce transition costs; (2) demonstration-based data provides leverage in international standard-setting negotiations; (3) integrated financial frameworks can alleviate private-sector burdens and broaden access to capital; (4) learning-based regulatory systems can enhance stakeholder acceptance and strengthen ecosystem trust.

Ultimately, three key insights emerge: (1) the sequencing of policy and technology is context-dependent, with cycle intensity determined by the alignment of four conditions;

(2) the technology–institution cyclic theory offers the most compelling explanation for eco-friendly transitions in shipping and shipbuilding; (3) regulation functions as enabling infrastructure rather than a constraint, with national models shaping the pathways, costs, and competitiveness of the transition. These insights inform practical strategies that enable major shipbuilding nations, including Korea, to minimize transition costs while maintaining long-term competitiveness under the IMO’s decarbonization framework.

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Abbreviations

The following abbreviations are used in this manuscript:

IMO	International Maritime Organization
ISO	International Organization for Standardization
IEC	International Electrotechnical Commission
GHG	Greenhouse Gas
GI	Green Innovation (Fund/Program, Japan)
LNG	Liquefied Natural Gas
SCR	Selective Catalytic Reduction
EU	European Union
CCUS	Carbon Capture, Utilization, and Storage
TD	Technological Determinism
SST	Social Shaping of Technology
MLP	Multi-Level Perspective
SNM	Strategic Niche Management
ALS	Air Lubrication System
JRTT	Japan Railway Construction, Transport and Technology Agency
MOF	Ministry of Oceans and Fisheries (Republic of Korea)
TRL	Technology Readiness Level (Technological Maturity)
TCO	Total Cost of Ownership (Fuel and Bunkering Systems)
FGIs	Focus Group Interviews (Expert discussions to address identified gaps)

References

1. Chircop, A.; Shan, D. Governance of international shipping in the era of decarbonization: New challenges for the IMO? In *Maritime Law in Motion*; Mukherjee, P.K., Mejia, M.Q., Xu, J., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 97–113. [[CrossRef](#)]
2. IMO. *Initial IMO Strategy on Reduction of GHG Emissions from Ships, Shipping*; International Maritime Organization: London, UK, 2018.
3. IMO. *2023 IMO Strategy on Reduction of GHG Emissions from Ships*; International Maritime Organization: London, UK, 2023.

4. Sim, M.; Lee, J.; Kim, Y.; Jung, D.; Lee, C. Strategic integration of data envelopment analysis and Back-casting theories for zero-emission transition in global container shipping companies: Pathways and frameworks. *Front. Mar. Sci.* **2025**, *12*, 1442572. [CrossRef]
5. Available online: <https://green-innovation.nedo.go.jp/en/about/> (accessed on 11 September 2025).
6. Available online: https://www.gov.cn/lianbo/bumen/202501/content_7000040.htm?utm_ (accessed on 11 September 2025).
7. Dafoe, A. On technological determinism: A typology, scope conditions, and a mechanism. *Sci. Technol. Hum. Values* **2015**, *40*, 1047–1076. [CrossRef]
8. Bimber, B. Karl Marx and the three faces of technological determinism. *Soc. Stud. Sci.* **1990**, *20*, 333–351. [CrossRef]
9. Williams, R.; Edge, D. The social shaping of technology. *Res. Policy* **1996**, *25*, 865–899. [CrossRef]
10. Hallström, J. Embodying the past, designing the future: Technological determinism reconsidered in technology education. *Int. J. Technol. Des. Educ.* **2022**, *32*, 17–31. [CrossRef]
11. McLuhan, M. *Understanding Media: The Extensions of Man*; McGraw-Hill: New York, NY, USA, 1964; p. 2.
12. Hauer, T. Technological determinism and new media. *Int. J. Engl. Lit. Soc. Sci.* **2017**, *2*, 239174.
13. Meyer, J.W.; Rowan, B. Institutionalized organizations: Formal structure as myth and ceremony. *Am. J. Sociol.* **1977**, *83*, 340–363. [CrossRef]
14. DiMaggio, P.J.; Powell, W.W. The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. *Am. Sociol. Rev.* **1983**, *48*, 147–160. [CrossRef]
15. Scott, W.R. Lords of the dance: Professionals as institutional agents. *Organ. Stud.* **2008**, *29*, 219–238. [CrossRef]
16. Currie, W.L. Institutional Theory of Information Technology. In *The Oxford Handbook of Management Information Systems: Critical Perspectives and New Directions*; Galliers, R.D., Currie, W.L., Eds.; Oxford University Press: Oxford, UK, 2011. [CrossRef]
17. Alexander, E.A. The effects of legal, normative, and cultural-cognitive institutions on innovation in technology Alliances. *Manag. Int. Rev.* **2012**, *52*, 791–815. [CrossRef]
18. Roszkowska-Menkes, M. Institutional theory. In *Encyclopedia of Sustainable Management*; Idowu, S.O., Schmidpeter, R., Capaldi, N., Zu, L., Del Baldo, M., Abreu, R., Eds.; Springer: Cham, Switzerland, 2023; pp. 1983–1990. [CrossRef]
19. Friedland, R.; Alford, R. Bringing society back In: Symbols, Practices, and Institutional Contradictions. In *The New Institutionalism in Organizational Analysis*; Powell, W.W., DiMaggio, P.J., Eds.; University of Chicago Press: Chicago, IL, USA, 1991; pp. 232–266.
20. Battilana, J.; Leca, B.; Boxenbaum, E. How Actors Change Institutions: Towards a Theory of Institutional Entrepreneurship. *Acad. Manag. Ann.* **2009**, *3*, 65–107. [CrossRef]
21. Garud, R.; Hardy, C.; Maguire, S. Institutional entrepreneurship. In *Encyclopedia of Creativity, Invention, Innovation and Entrepreneurship*; Carayannis, E.G., Ed.; Springer: New York, NY, USA, 2013; pp. 1069–1074.
22. Meckling, J. Making industrial policy work for decarbonization. *Glob. Environ. Polit.* **2021**, *21*, 134–147. [CrossRef]
23. Geels, F.W. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Res. Policy* **2002**, *31*, 1257–1274. [CrossRef]
24. Geels, F.W.; Schot, J. Typology of sociotechnical transition pathways. *Res. Policy* **2007**, *36*, 399–417. [CrossRef]
25. Kemp, R.; Schot, J.; Hoogma, R. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technol. Anal. Strateg. Manag.* **1998**, *10*, 175–198. [CrossRef]
26. Ahern, D. Regulatory lag, regulatory friction and regulatory transition as FinTech disenablers: Calibrating an EU response to the regulatory sandbox phenomenon. *Eur. Bus. Org. Law Rev.* **2021**, *22*, 395–432. [CrossRef]
27. Ahern, D. The new anticipatory governance culture for innovation: Regulatory foresight, regulatory experimentation and regulatory learning. *Eur. Bus. Org. Law Rev.* **2025**, *26*, 241–283. [CrossRef]
28. Mallouppas, G.; Yfantis, E.A. Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. *J. Mar. Sci. Eng.* **2021**, *9*, 415. [CrossRef]
29. Sideri, O.; Papoutsidakis, M.; Lilas, T.; Nikitakos, N.; Papachristos, D. Green shipping onboard: Acceptance, diffusion & adoption of LNG and electricity as alternative fuels in Greece. *J. Shipp. Trade* **2021**, *6*, 9. [CrossRef]
30. Harahap, F.; Nurdawati, A.; Conti, D.; Leduc, S.; Urban, F. Renewable marine fuel production for decarbonised Maritime shipping: Pathways, policy measures and transition dynamics. *J. Clean. Prod.* **2023**, *415*, 137906. [CrossRef]
31. Caprace, J.-D.; Marques, C.H.; Assis, L.F.; Lucchesi, A.; Pereda, P.C. Sustainable shipping: Modeling technological pathways toward net-zero emissions in maritime transport (Part I). *Sustainability* **2025**, *17*, 3733. [CrossRef]
32. Chen, Y.; Cheng, K. Decarbonizing arctic shipping: Governance pathways and future directions. *Front. Mar. Sci.* **2025**, *12*, 1489091. [CrossRef]
33. Shi, J.; Zhu, Y.; Feng, Y.; Yang, J.; Xia, C.; Prompt, A. Decarbonization pathway for shipping: Green hydrogen, ammonia, and methanol production and utilization in marine engines. *Atmosphere* **2023**, *14*, 584. [CrossRef]
34. Sun, L.; Zhang, Y.; Ma, F.; Ji, F.; Xiong, Y. Energy and speed optimization of inland battery-powered ship with considering the dynamic electricity price and complex navigational environment. *Energy Rep.* **2023**, *9*, 293–304. [CrossRef]

35. Qi, J.; Wang, S. LNG Bunkering Station deployment problem—A case study of a Chinese container shipping network. *Mathematics* **2023**, *11*, 813. [CrossRef]
36. Wang, S.; Qi, J.; Laporte, G. Governmental subsidy plan modeling and optimization for liquefied natural gas as fuel for maritime transportation. *Transp. Res. B Methodol.* **2022**, *155*, 304–321. [CrossRef]
37. Peng, Y.; Zhao, X.; Zuo, T.; Wang, W.; Song, X. A systematic literature review on port LNG bunkering station. *Transp. Res. Part D Transp. Environment* **2021**, *91*, 102704. [CrossRef]
38. Han, M.; Zhang, J.; Chu, W.; Chen, J.; Zhou, G. Research progress and prospects of marine oily wastewater treatment: A review. *Water* **2019**, *11*, 2517. [CrossRef]
39. COP26: Clydebank Declaration for Green Shipping Corridors. Available online: <https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors> (accessed on 4 July 2025).
40. Available online: https://assets.ctfassets.net/gk3lrimlph5v/7nPAD2U46GMOv5T6Zu2cP/7d82ab6a75862842547e0fe55c27959b/gmf_impactreport_digital_finalUpdate.pdf (accessed on 4 July 2025).
41. Molinder, J.; Karlsson, T.; Enflo, K. More power to the people: Electricity adoption, technological change, and labor conflict. *J. Econ. Hist.* **2021**, *81*, 481–512. [CrossRef]
42. Lai, K.; Wong, C.W.Y.; Cheng, T.C.E. Institutional isomorphism and the adoption of information technology for supply chain management. *Comput. Ind.* **2006**, *57*, 93–98. [CrossRef]
43. Scott, W.R. *Institutions and Organizations*. SAGE Publications: Thousand Oaks, CA, USA, 1995.
44. Meti, N. Green Innovation Fund toward Achieving Carbon Neutrality by 2050: Establishment of a 2 Trillion Yen Fund to Support R&D, Demonstration and Social Deployment in Priority Sectors. 2021. Available online: https://www.meti.go.jp/english/policy/energy_environment/global_warming/gifund/index.html (accessed on 11 September 2025).
45. National Development and Reform Commission (NDRC). Release of the 2024 Edition of the Green Technology Promotion Catalog, Listing 112 Advanced Green Technologies Across Seven Sectors, and Directing Financial Support and Commercialization. 2024. Available online: https://www.ndrc.gov.cn/xxgk/zcfb/fzggwl/202312/t20231229_1362999.html (accessed on 1 October 2025).
46. Li, W.; Hu, Z. Pathways in the governance of shipping decarbonization from the perspective of balancing the Conflicting interests. *Front. Mar. Sci.* **2024**, *11*, 1479528. [CrossRef]
47. European Commission. Decarbonising Maritime Transport—FuelEU Maritime. 2024. Available online: https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en (accessed on 11 September 2025).
48. Etzkowitz, H.; Leydesdorff, L. The Dynamics of Innovation: From National Systems and “Mode 2” to a Triple Helix of University–Industry–Government Relations. *Res. Policy* **2000**, *29*, 109–123. [CrossRef]
49. Shaoan, H.; Kainan, H. The co-evolution of technology and institution. In *Dictionary of Contemporary Chinese Economics*; Hong, Y., Ed.; Springer: Singapore, 2025; pp. 449–451. [CrossRef]
50. Available online: https://www.meti.go.jp/english/policy/energy_environment/global_warming/ggs2050/ (accessed on 11 September 2025).
51. Ozawa, A.; Tsani, T.; Kudoh, Y. Japan’s pathways to achieve carbon neutrality by 2050—Scenario analysis using an energy modeling methodology. *Renew. Sustain. Energy Rev.* **2022**, *169*, 112943. [CrossRef]
52. Sokolowski, M.M.; Kurokawa, S. Energy justice in Japan’s energy transition: Pillars of just 2050 carbon neutrality. *J. World Energy Law Bus.* **2022**, *15*, 183–192. [CrossRef]
53. Japan. National Research and Development Corporation New Energy and Industrial Technology Development Organization Act (Act No. 145 of 2002). 2002. Available online: https://www.mlit.go.jp/en/maritime/GHG_roadmap_en.html (accessed on 11 September 2025).
54. Available online: <https://ammoniaenergy.org/articles/interim-guidelines-released-for-safe-ammonia-imports-in-japan/> (accessed on 11 September 2025).
55. Available online: https://www.jrtt.go.jp/ship/outline/?utm_ (accessed on 11 September 2025).
56. Jaques, B. Japanese Zero Emission Ship Concepts Unveiled. 2020. Available online: <https://www.seatrade-maritime.com/environmental/japanese-zero-emission-ship-concepts-unveiled> (accessed on 1 February 2021).
57. Kato, E.; Kurosawa, A. Evaluation of Japanese energy system toward 2050 with TIMES-Japan—deep decarbonization pathways. *Energy Procedia* **2019**, *158*, 4141–4146. [CrossRef]
58. Available online: https://green-innovation.nedo.go.jp/en/article/ammonia-fueled-tugboat/?utm_ (accessed on 11 September 2025).
59. Available online: https://www.j-eng.co.jp/en/news/2023/20230516.html?utm_ (accessed on 11 September 2025).
60. Available online: https://www.yanmar.com/global/about/technology/technical_review/2022/08_6.html?utm_ (accessed on 11 September 2025).
61. Available online: https://www.meti.go.jp/press/2024/02/20250218001/20250218001.html?utm_ (accessed on 11 September 2025).

62. Ministry of Land, Infrastructure, Transport and Tourism (MLIT); Maritime Bureau. Guidelines for Handling Biofuels in Ships. 2024. Available online: <https://www.mlit.go.jp/report/press/content/001597437.pdf> (accessed on 12 September 2025).
63. Available online: https://www.mol.co.jp/en/info/article/2025/0404b.html?utm_ (accessed on 11 September 2025).
64. Available online: https://www.mol.co.jp/en/pr/2021/21057.html?utm_ (accessed on 11 September 2025).
65. Available online: https://www.mhi.com/news/211214.html?utm_ (accessed on 11 September 2025).
66. Available online: https://en.osy.co.jp/shipbuilding/technology/?utm_ (accessed on 11 September 2025).
67. Kawamata, S.; Watanabe, Y.; Unseki, T. Development of onboard CO₂ Capture System: “CC-Ocean Project” for Verification Testing of Onboard CO₂ Capture System. *Mitsubishi Heavy Ind. Tech. Rev.* **2022**, *59*, 1–7.
68. Han, J. Imabari maritime cluster: A case analysis of Japan maritime cluster. *J. Shipp. Logist.* **2018**, *34*, 695–710. [CrossRef]
69. Kanetsuna, M.; Miyaji, K.; Sato, T. R&D and inter-firm knowledge flow in Japan’s shipbuilding industry: Comparative analysis of factors that promote knowledge flow between domestic and overseas partners. In *Management for Sustainable and Inclusive Development in a Transforming Asia*; Shioji, H., Adhikari, D.R., Yoshino, F., Hayashi, T., Eds.; Springer: Singapore, 2021; pp. 205–221.
70. Ministry of Industry and Information Technology (MIIT); National Development and Reform Commission (NDRC); Ministry of Finance (MOF); Ministry of Ecology and Environment (MEE); Ministry of Transport (MOT). Action Plan for Green Development of Shipbuilding Industry (2024–2030). 2024. Available online: https://www.gov.cn/zhengce/zhengceku/202312/content_6923175.htm (accessed on 1 October 2025).
71. Available online: https://sqzc.gd.gov.cn/rdzt/lsfz/gjzc/content/post_4339074.html?utm_ (accessed on 12 September 2025).
72. National Development and Reform Commission (NDRC). Guidance Catalogue for Green Industries (2019 Edition). 2019. Available online: <https://www.ndrc.gov.cn> (accessed on 12 September 2025).
73. National Development and Reform Commission (NDRC); Ministry of Industry and Information Technology (MIIT); Ministry of Natural Resources (MNR); Ministry of Ecology and Environment (MEE). Green and Low-Carbon Transformation Industry Guidance Catalogue (2024 Edition). 2024. Available online: https://www.gov.cn/zhengce/zhengceku/202403/content_6935418.htm (accessed on 12 September 2025).
74. Liu, J.; Yan, X.; Liu, C.; Fan, A.; Ma, F. Developments and applications of green and intelligent inland vessels in china. *J. Mar. Sci. Eng.* **2023**, *11*, 318. [CrossRef]
75. Available online: https://lngprime.com/asia/qatarenergy-hudong-zhonghua-seal-deal-for-giant-lng-carriers/101925/?utm_ (accessed on 12 September 2025).
76. Yang, K. Application Status and Prospect of Inland River LNG-Fueled Ships in China. 2019. Available online: https://www.sohu.com/a/326031720_269757 (accessed on 1 January 2023).
77. Available online: https://rethinkingplastics.eu/pilot-projects-en/53-improving-ship-waste-management-in-chinese-commercial-ports?utm_ (accessed on 12 September 2025).
78. Ministry of Oceans and Fisheries (MOF). Green ship-K supply Implementation Plan. Available online: <https://www.mof.go.kr/doc/ko/selectDoc.do?bbsSeq=90&docSeq=49969&menuSeq=485> (accessed on 13 September 2025).
79. Ministry of Oceans and Fisheries (MOF); Ministry of Trade, Industry and Energy (MOTIE). 2030 GreenShip-K Promotion Strategy, to Dominate the Global Green Ship Market. Available online: <https://www.mof.go.kr/page/en/selectPage.do?menuSeq=1588&pageSeq=1017&listUpdtDt=2025-10-21++10%3A00> (accessed on 13 September 2025).
80. Available online: <https://www.law.go.kr/%EB%B2%95%EB%A0%B9/%ED%99%98%EA%B2%BD%EC%B9%9C%ED%99%94%EC%A0%81%EC%84%A0%EB%B0%95%EC%9D%98%EA%B0%9C%EB%B0%9C%EB%B0%8F%EB%B3%B4%EA%B8%89%EC%B4%89%EC%A7%84%EC%97%90%EA%B4%80%ED%95%9C%EB%B2%95%EB%A5%A0> (accessed on 1 July 2025).
81. Jeong, H. A research on establishing preparedness strategy for domestic shipping industry through SWOT analysis on ‘eco-ship law’. *J. Soc. Sci.* **2023**, *42*, 5–32. [CrossRef]
82. Ahn, J. A Study on Improvement for Greenship Certification Scheme to Achieve Net-Zero. *J. Soc. Nav. Archit. Korea* **2022**, *59*, 372–384. [CrossRef]
83. Available online: <https://www.mof.go.kr/doc/ko/selectDoc.do?docSeq=60244&menuSeq=1067&bbsSeq=81> (accessed on 5 June 2025).
84. Available online: <https://www.mof.go.kr/doc/ko/selectDoc.do?docSeq=60234&listUpdtDt=2025-02-05++10:00&menuSeq=971&bbsSeq=10> (accessed on 5 June 2025).
85. Yoo, S.; Kim, G.; Mun, H.; Bae, G.; Kim, D.K. Analysis of Regional Economic Ripple Effects of Constructing LNG Bunkering Infrastructure at Busan Port. *Environ. Resour. Econ. Rev.* **2024**, *33*, 291–314. [CrossRef]
86. Lim, H.; Dahal, P.; Pan, M.; Karcz, J.; Fialkoff, M.; Theiss, T.; Kass, M.; Busch, I. *Republic of Korea–United States Green Shipping Corridor Prefeasibility Study: Cargo Flows*, ORNL/SPR-2023/3099; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2023.
87. Lee, T.; Nam, H. A study on green shipping in major countries: In the view of shipyards, shipping companies, ports, and policies. *Asian J. Shipp. Logist.* **2017**, *33*, 253–262. [CrossRef]
88. Yun, Y.; Ahn, J.; Lee, J.; Lee, K. A study on the validity of greenship-certification scheme considering carbon Intensity indicator. *J. Shipp. Logist.* **2024**, *40*, 373–390. [CrossRef]

89. Choi, C.H.; Yu, S.; Han, I.S.; Kho, B.K.; Kang, D.G.; Lee, H.Y.; Seo, M.S.; Kong, J.W.; Kim, G.; Ahn, J.W.; et al. Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat. *Int. J. Hydrog. Energy* **2016**, *41*, 3591–3599. [CrossRef]
90. Available online: https://www.komeri.re.kr/bbs/board.php?bo_table=press&wr_id=216&page=1 (accessed on 4 July 2025).
91. Available online: <https://www.krs.co.kr/kor/Webzine/View.aspx?WMDR=413&WCDR=7240> (accessed on 4 July 2025).
92. Available online: <https://www.yna.co.kr/view/AKR20241121070801051> (accessed on 1 July 2025).
93. Available online: https://www.krs.co.kr/eng/BBS/BF_View.aspx?MRID=558&BF_ROWID=CNYNXzgo8oBOFZ9EcWoU5Q== (accessed on 4 July 2025).
94. Available online: <https://www.hmm21.com/company/esg/sustainability-strategy.do?lang=en> (accessed on 4 July 2025).
95. Available online: <https://kats.go.kr/mobile/content.do?cmsid=482&skin=/mobile/&mode=view&page=&cid=24688> (accessed on 4 July 2025).
96. Available online: <https://www.law.go.kr/lsSc.do?query=%ED%99%98%EA%B2%BD%EC%B9%9C%ED%99%94%EC%A0%81%20%EC%84%A0%EB%B0%95%EC%9D%98%20%EA%B0%9C%EB%B0%9C%20%EB%B0%8F%20%EB%B3%B4%EA%B8%89%20%EC%B4%89%EC%A7%84%EC%97%90%20%EA%B4%80%ED%95%9C%20%EB%B2%95%EB%A5%A0#undefined> (accessed on 4 July 2025).

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