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Strategic Pathways to Alternative Marine Fuels: Empirical Evidence from Shipping Practices in South Korea

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Abstract: This study investigates the transition to a sustainable shipping industry within the framework of the IMO's 2050 carbon neutrality objective, focusing on sociotechnical systems analysis. This research delves into the sustainable paradigm shift towards alternative marine fuels, such as LNG, methanol, ammonia, and hydrogen, from a sociotechnical transition perspective, analyzing the multilevel perspective challenges and opportunities. Specifically, it scrutinizes the implications of adopting these alternative fuels for global shipping, identifying technical uncertainties, financial constraints, and infrastructure needs. Through a comprehensive review of the existing literature on ship emissions and alternative fuels, coupled with sociotechnical transition theory, this study addresses the multifaceted challenges and opportunities in meeting the IMO's environmental objectives. It emphasizes the necessity of collaborative governance, innovative niche strategies, and a holistic approach to leverage the current window of opportunity in facilitating the maritime industry's transition to sustainable fuel options. Finally, this research enhances our understanding of the intricate interplay between technological, social, industrial, and cultural dynamics in the greening of shipping, and offers insights into the strategic adoption of environmentally friendly marine fuels for a sustainable future.

Keywords: green shipping; IMO 2050; alternative marine fuels; sociotechnical systems analysis; sustainable future

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1. Introduction

1.1. Background of Study

The International Maritime Organization (IMO) adopted the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973 to prevent marine pollution caused by ships. The Protocol of 1997 (Annex VI—Regulations for the Prevention of Air Pollution from Ships) within MARPOL was adopted in 1997 and entered into force in 2005. Under MARPOL Annex VI, the IMO limits the amount of sulfur oxides (SO_x) and nitrogen oxides (NO_x) emitted by ships during operation and prohibits the emission of ozone [1]. In addition, in July 2011 the IMO amended MARPOL Annex VI to introduce the Energy Efficiency Design Index (EEDI) for new ships (new builds) and the Energy Efficiency Management Plan (SEEMP) for all ships. This amendment marked the first formal institutionalization and management of greenhouse gas (GHG) emissions from ships in relation to energy efficiency obligations. In 2018, the IMO adopted the Initial IMO Strategy for the reduction in GHG emissions from ships, setting a target of a 50% reduction in GHG emissions from international shipping by 2050 (compared to 2008 levels). At the 80th session of the Marine Environment Protection Committee (MEPC) in 2023, the IMO

adopted the '2023 IMO GHG Strategy', which revised the targets of the previous Initial Strategy and set challenging targets and strategies to achieve net-zero GHG emissions from shipping by 2050 [2].

To address increasingly stringent global environmental regulations, global shipping companies are preparing distinct alternatives as long-term measures, such as vessel hull shape modifications, adjusting course navigation, and scrapping old ships. These measures are aimed at achieving environmental, social, and corporate governance (ESG) management within shipping companies by reducing the emission of sulfur oxides, an air pollutant from ships. In addition, global shipping companies are also implementing short-term measures, such as (1) installing scrubbers while still using bunker C fuel, (2) switching to low-sulfur fuel oil (LSFO) or marine gas oil (MGO) instead of high-sulfur heavy fuel oil (HFO), and (3) transitioning to alternative marine fuels, such as liquefied natural gas (LNG), methanol, ammonia, hydrogen, etc. [3].

These efforts of global shipping companies have increasingly led to the realization that addressing climate change requires transitions from existing fossil fuel-based energy and shipping transport systems toward low-carbon systems based on 'sustainability green' technologies, new infrastructures, user practices, policies, and cultural meanings [4–6]. In this context, system transition is based on the multilevel perspective (MLP) of sociotechnical transition theory. The MLP framework has been developed by sustainability transition researchers [7,8] with the goal of understanding system changes that encompass 'long-term, multidimensional, fundamental change processes in which existing sociotechnical systems transition to more sustainable ways' [9,10]. It encompasses multidimensional developments at three analytical levels: niches, sociotechnical regimes, and an exogenous sociotechnical landscape. In essence, changes at the landscape level create pressures on the regime, and the destabilization of the regime creates windows of opportunity for the diffusion of niche innovations [6]. This logic is the theoretical framework that will be central to this study. Through the MLP framework, we explore breakthroughs from the shipping industry to green innovation in various aspects of the sociotechnical regime (technology, politics, culture, industrial environment, and infrastructure).

We posit that global competitiveness can be secured by transitioning from traditional fossil fuels to environmentally friendly alternatives in accordance with the enhanced IMO 2023 strategy; however, Korean shipping companies are weaker than their global counterparts and are somewhat passive in the sustainability transition. Therefore, we consider that academic research is needed to induce system transition through the sociotechnical transition theory from an MLP, in which domestic and foreign institutions, stakeholders, and the maritime industry are combined with various factors of political, economic, and technological change. To address this, we examine the opportunities and challenges of the transition to a greener maritime industry through the lens of sociotechnical transition theory, and ultimately anticipate an important contribution to the systemic transition towards a sustainable and eco-friendly shipping industry.

1.2. Literature Review

GHG emissions from ships have been highlighted as a source of global GHG emissions, and the share of maritime transport in global emissions is expected to increase further. To decarbonize the shipping industry, the IMO has been actively publishing strategies and implementing comprehensive regulations to reduce emissions related to ships. The IMO has been working to reduce ship-related NO_x and SO_x emissions by establishing Emission Control Areas (ECAs) in various regions around the world. Additionally, the IMO has defined short-, medium-, and long-term measures through the IMO Strategy for the reduction in GHG emissions from ships. Following the publication of the IMO Initial Strategy in 2018, the 2023 IMO Strategy was recently released, further enhancing regulatory standards and levels of ambition compared to the previous IMO Initial Strategy. During the 80th session of the MEPC in 2023, indicative checkpoints were established for achieving net-zero GHG emissions from the international shipping industry. These checkpoints

include reducing annual GHG emissions from international shipping by at least 20% by 2030, aiming for 30% compared to the 2008 levels; reducing annual GHG emissions from international shipping by at least 70% by 2040, aiming for 80% compared to the 2008 levels; and, finally, peaking GHG emissions from international shipping as soon as possible and achieving net-zero emissions by or around 2050. The strategy specifically outlines a plan to transition at least 5% (with an aim of 10%) of total international shipping energy to zero or near-zero technologies and fuels by 2030. This strategy appears to directly regulate emissions to achieve the 2050 net-zero target; the 2030 target will likely be strengthened by the IMO's forthcoming medium-term measures for GHG reduction and the marine fuel standard regime [11].

Thus, the IMO is steadily strengthening its environmental standards for the shipping industry. Nevertheless, according to Bach et al. (2023), while GHG-related legislation has been implemented to some extent, its scope remains limited, with the regulatory focus primarily directed towards air pollution control. The specifics of proposed short- and medium-term GHG regulations, such as the Energy Efficiency Design Index (EEXI) for existing ships, the updated SEEMP, and the Carbon Intensity Index (CII), are still under negotiation, and the effectiveness of these measures is yet to be determined [12]. Liu et al. (2024) stated that it is imperative for the shipping industry to adopt sustainable solutions that minimize the environmental impact stemming from its high-carbon-emissions characteristics [13]. Bilgili (2023) stated that various methods, such as hull optimization, engine conversion, alternative propulsion systems, and alternative energy sources, have been proposed and implemented over the years to achieve a sustainable environment in the shipping industry [14]. In particular, Xing et al. (2021) and Bilgili (2021) observed that the 2023 IMO GHG Strategy, which has been further strengthened from the Initial IMO Strategy in 2018, shows a significant increase in interest in alternative marine fuels. Alongside numerous technical and operational measures, the strategy aims to achieve carbon-free shipping by 2050 [15]. Concurrently, alternative marine fuels are being adopted and utilized as crucial solutions to mitigate ship-related air pollutants; research on these alternative marine fuels by international organizations, such as the IMO, is growing and becoming increasingly important [16]. In this context of the increasing interest in and importance of alternative marine fuels, many researchers [17–20] have conducted technical reviews of alternative marine fuels to assess their prospects for application in the shipping industry and their technical capabilities, such as effectiveness, efficiency, and applicability.

However, according to Hellström (2024), alternative marine fuels are still undergoing various reviews regarding their future applicability. While these fuels hold the greatest potential for reducing carbon emissions, they are expensive, and there is significant uncertainty regarding the feasibility of investing in these technologies. Furthermore, despite the increasing knowledge about the properties and potential of alternative marine fuels, there is no consensus on which fuels are the most suitable for each sector of the shipping industry in the near and long terms [21]. Furthermore, Bilgili (2023) stated that the global use of alternative marine fuels is still in its early stages, primarily due to several key concerns. These include technical and environmental incompatibilities, limitations in infrastructure, cost issues, and insufficient levels of seafarer education [14].

Previous studies on GHG emissions from ships have aimed to overcome the environmental challenges facing the shipping industry by exploring the use of alternative marine fuels. Most of these studies [13–21] have primarily focused on the technical aspects of fuel switching. While they have generally supported the transition of the shipping industry to eco-friendly sustainable marine fuels, they have also raised concerns about various challenges and uncertainties. We point out that there has been a lack of research on the social considerations of how the shipping industry can go green from a multilevel perspective. Therefore, this study explores comprehensive strategies and measures with which to realize a sustainable shipping industry through social, technological, industrial, and cultural transformations across the entire shipping industry. Ultimately, the recommendations proposed

in this study will extend beyond ecological changes in the shipping industry and strive for sustainable transformations through social structures and technological innovations.

1.3. Research Approach Derived from Text Mining

1.3.1. Identifying Research Trends by Timing IMO Regulations through Text Mining

Despite substantial social and technological efforts, the introduction of alternative marine fuels into the shipping industry encounters numerous challenges, underscoring a pivotal moment in the transition to a sustainable shipping sector. Achieving sustainability in the shipping industry requires a comprehensive, multilevel perspective encompassing technical and social dimensions. The sociotechnical systems perspective emphasizes the interconnectedness of the shipping industry with various spheres of political, economic, and technological change, suggesting that the confluence of these factors drives systemic shifts. Government policies, technological advancements, and shifts in industrial practices as well as culture synergistically influence the entire sociotechnical system. Therefore, as an initial research step, examining the current literature on sustainable shipping can offer valuable insights into the status and dynamics of the sociotechnical system.

For this purpose, abstracts of a total of 509 high-quality articles were collected from the Web of Science (WoS) by using the keywords 'shipping + GHG + emission' from 1 January 2008 to 31 December 2023. A statistical graph of the frequency of the collected abstracts is shown in Figure 1. Analyzing the amount of published literature can aid in comprehending shifts in research focal points during a particular timeframe and anticipating future developmental trends [22].

Type	Key word	Survey Year	Survey Media	Total (Unit: ea)
High-quality article	shipping, GHG, emission	2008–2023	Web of Science	509

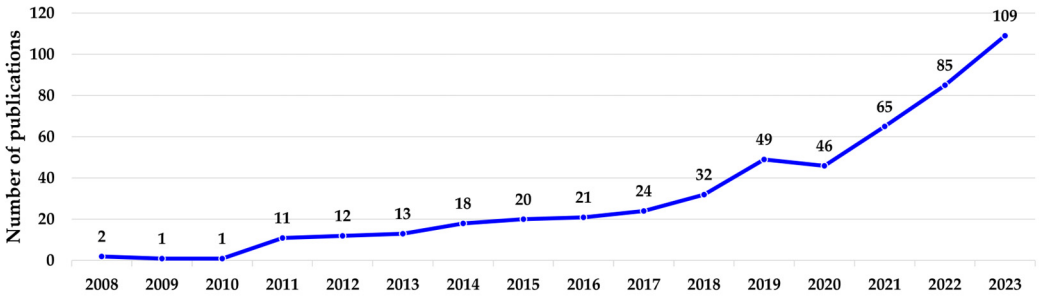

Figure 1. Trends of frequency in the abstracts of WoS articles on GHG emissions in the shipping industry (2008–2023).

Subsequently, the collected data were integrated with the implementation of the IMO environmental regulations and strategies. To ensure a clear time series separation, we utilized the IMO's baseline year and strategy launch date as reference points. Specifically, the first point was 2008, designated as the baseline year for the IMO's environmental regulations. The second point was 2013, marking the implementation of direct air pollution reduction regulations, such as the EEDI and SEEMP. The third point was 2018, signifying the establishment of the IMO GHG reduction initial strategy. Lastly, the fourth point was 2023, denoting the establishment of the IMO GHG reduction 2030 strategy. Building upon this segmentation, we conducted an ego network analysis focusing on 'marine fuel' by using the 509 valid abstracts from WOS articles, employing NetMiner version 4.5.0 (Cyram Inc., Seongnam, Republic of Korea) as the network analysis software [23]. The results are shown in Figure 2.

The nodes in Figure 2 were colored as follows: grey for general words, black for conventional marine fuels (fossil fuels, HFO, etc.), blue for alternative marine fuels (biofuel, ammonia, methane, LNG, etc.), and green for technical measures with which to reduce GHG emissions. The size reflected the frequency, and the thickness of the link also indicated the number of connections. Upon analyzing trends in the abstracts of the WoS articles on

GHG emissions in the shipping industry, distinct patterns emerged across the different periods. In the first period (2008–2013), the focus was primarily on fossil fuels. During the second period (2014–2018), the emphasis shifted towards technical and operational measures aimed at reducing air pollution from ships. Finally, in the third period (2019–2023) there was a notable surge in interest in new fuels, such as hydrogen, biofuels, ammonia, and methanol, which are considered alternative marine fuels.

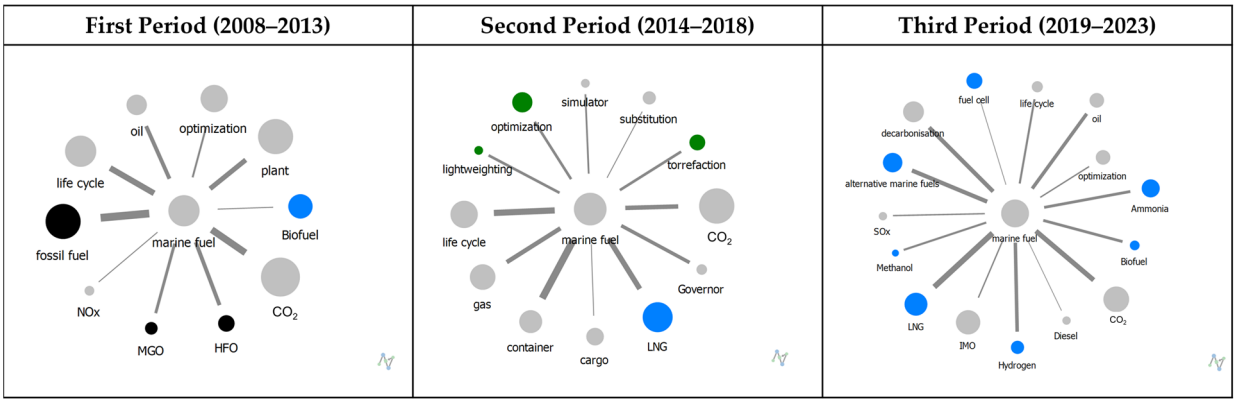

Figure 2. Result of an ego network analysis of WoS articles focusing on 'Marine Fuel' by timing the IMO's regulations.

Concurrent with the progression of environmental regulations by the IMO, there has been a continuous transition away from fossil fuels towards greener and more sustainable alternative marine fuels, accompanied by ongoing research activities in this field. Previous literature reviews [13–21] and research trends derived from text mining show that research on GHG emissions from ships has mainly focused on technical aspects (types, applicability, and efficiency of alternative marine fuels, associated infrastructure requirements, etc.). The sustainable transition of the shipping industry remains challenging from many perspectives. In other words, under the green system transformation that the IMO is heading towards, there is still a lot of unknown space from various perspectives before the shipping industry can reach a sustainable green transition. Therefore, by identifying and addressing potential blind spots from a multilevel perspective, this study aims to facilitate a sustainable system shift in the shipping industry. By addressing this gap in the existing literature, the study contributes to the multifaceted discussion on decarbonizing ship-based air pollution.

1.3.2. Research Question Derived from Text Mining

Various pieces of research concerning various alternative marine fuels have been actively carried out in line with the IMO's aggressive environmental regulations. This means that government intervention, such as international environmental regulations, has become a factor promoting the sustainable transformation of the shipping industry, and that the expanding research on and introduction of new alternative marine fuels are likely to be driven by government policy support and economic factors affecting the entire social system of the shipping industry. In other words, as the share of new alternative marine fuels increases, the sustainable transformation of the shipping industry is developing in a new direction. Figure 3 shows the time series of the IMO's environmental regulations and research trends related to GHG emissions from ships. Despite the positive trend towards a new direction of research in the sociotechnical transition paradigm, uncertainties persist in terms of social, technological, industrial, and cultural aspects. These uncertainties must be addressed to adapt to the paradigm shift and achieve the ambitious environmental goals set by the IMO. Further research and efforts are necessary in order to overcome these challenges and adapt to the new paradigm. Therefore, exploring the challenges, opportunities, and niche innovations arising in leading the uncharted space towards the eco-friendly sustainable transition of the shipping industry into a new paradigm is

imperative. Figure 3 illustrates the research questions that belong to the unknown space to move towards a sustainable and eco-friendly shipping industry through a text mining analysis and literature review.

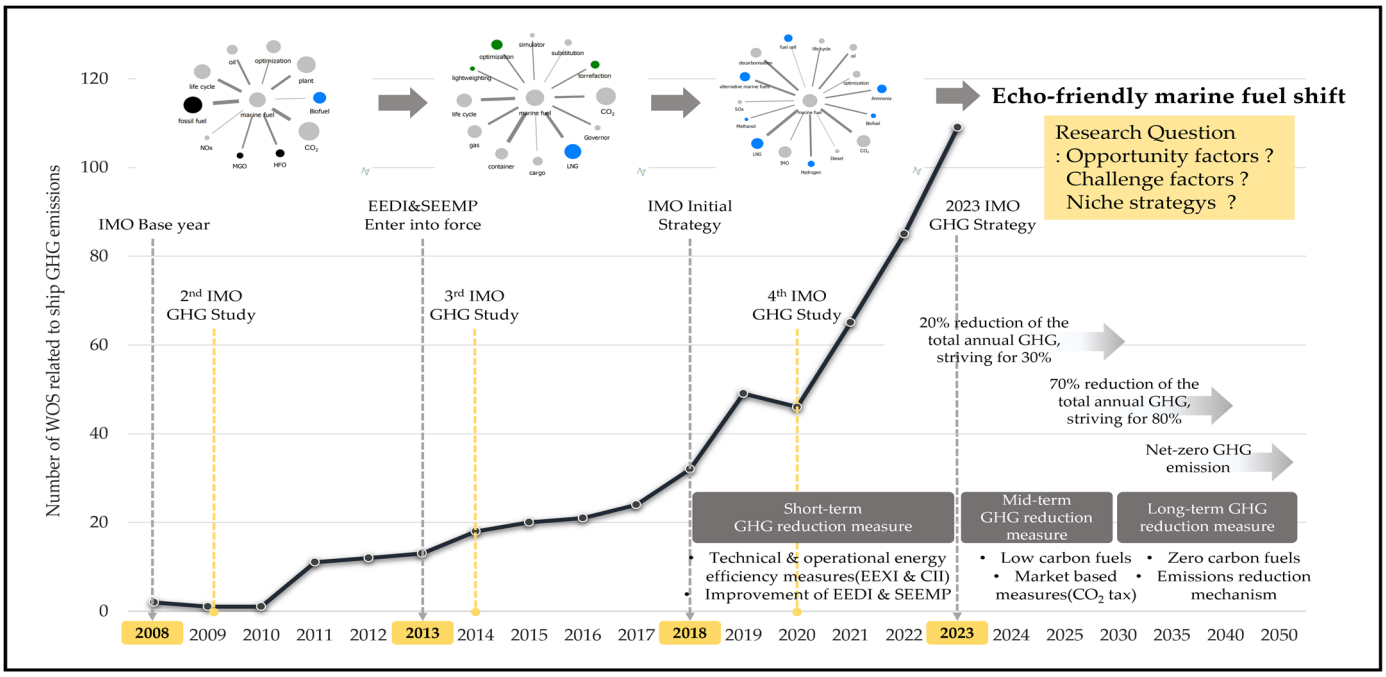

Figure 3. Research questions derived from text mining: the time series of the IMO's environmental regulations and research trends related to GHG emissions from ships.

Thus, the research questions involved the following:

1. What are the challenging factors in the shift to eco-friendly marine fuels?
2. What are the opportunities for the shift to eco-friendly marine fuels?
3. What is the Niche Innovations Strategy that integrates the opportunities and challenges of the shift to eco-friendly marine fuels?

This study is organized into five sections: Section 2 introduces the theoretical framework based on an MLP and presents the theoretical framework that we have modified to suit our research objectives. Section 3 describes the empirical results that answer our research questions. Section 4 discusses the main findings of the study in light of the proposed analytical framework. Finally, Section 5 draws conclusions and policy implications. The research process is illustrated in Figure 4.

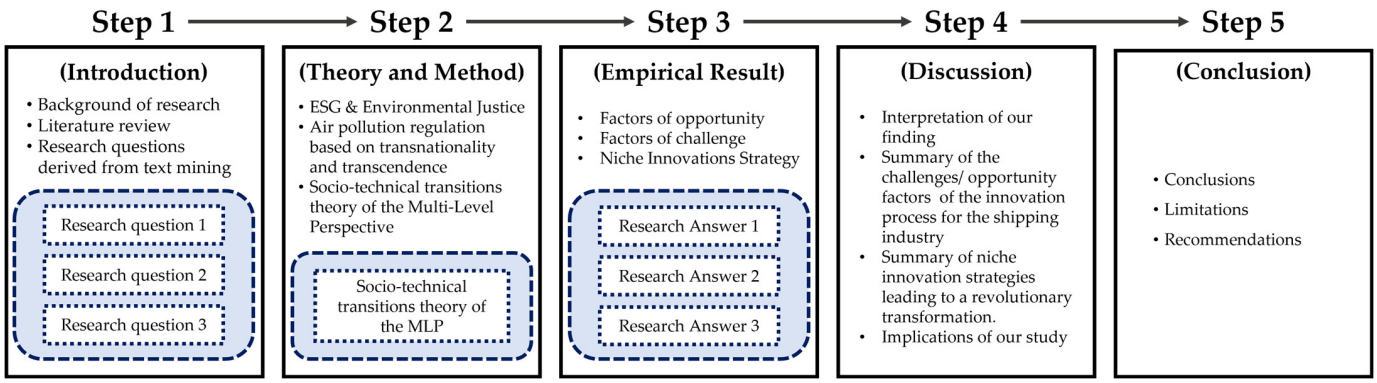

Figure 4. Process of research.

2. Theory and Method

2.1. Theory

2.1.1. Theory for Environmental Justice and ESG

By actively implementing ESG principles based on environmental justice theory, global shipping companies are leading the way in sustainable development and creating long-term economic value. By implementing ESG principles, global shipping companies are addressing environmental, sociotechnical, and managerial risks, seizing opportunities for a sustainable future, and enhancing their market competitiveness [24]. ESG practices, rooted in environmental justice theory, serve as a means for shipping companies to operate sustainably and equitably across the environmental, social, and governance domains. It is imperative for shipping companies to strategically adopt and implement ESG principles to fulfill their environmental responsibilities and promote environmental justice in the long term, thereby laying the groundwork for future generations [25]. In turn, by fulfilling their environmental responsibilities, shipping companies should achieve equitable distribution, which is a core principle of environmental justice, including minimizing GHG emissions from ships and preventing marine pollution [26]. Furthermore, by minimizing the impact of ships on the marine environment through the adoption of sustainable marine fuel technologies and efficient operational management, shipping companies should contribute to sustainable environmental management not only for the present, but also for future generations.

2.1.2. Theory of Air Pollution Regulation Based on Transnationality and Transboundary Principles

From a time series perspective, humanity has faced various environmental pollution problems caused by the use of coal fuel during the industrial revolution in the 18th and early 19th centuries, and, after the Second World War, with the development of the mass production and sale of automobiles, attention expanded to air pollution [27]. In particular, air pollution contributes to global warming, ozone depletion, and extreme weather events, presenting a common challenge that humanity must address through global or regional agreements. The necessity for internationally binding environmental agreements has been recognized through various milestones, including the Declaration of the United Nations Conference on the Human Environment in 1972, the Convention on Long-range Transboundary Air Pollution in Geneva in 1979, the Basel Convention on the Control of Transboundary movements of Hazardous Wastes in 1992, and the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [28]. In relation to the transnationality and transboundary nature of air pollution from ships, which is a key source theory for this study, the adoption of the SEEMP was extended to all ships engaged in international navigation at the 62nd session of the MEPC in 2011, following the amendment of Annex VI of MARPOL 73/78 to regulate GHG emissions from ships [29].

2.1.3. Sociotechnical Transition Theory of a Multilevel Perspective, including Window of Opportunity

Based on the air pollution from ships (based on transnationality and transboundary) and ESG as well as environmental justice theory, which is the core issue of shipping companies, the current shipping industry presents a huge social challenge for the environmental field. The solution to these problems can only be realized by deep structural changes in transport, energy, and other systems [4,30,31]. These systemic changes are often referred to as 'sociotechnical transitions' because they involve alterations to the overall configuration of the transport and energy systems, involving technologies, policy, markets, consumer practices, infrastructure, cultural meanings, and scientific knowledge [31,32]. Merchant ships are engaged in international voyages, so it is necessary to develop not only the physical forms of ships but also social factors, such as international norms, interest groups, and political, economic, and social forces [33]. Therefore, we propose providing a future-oriented solution for shipping companies through 'sociotechnical transitions', which

are complex and long-term processes consisting of multiple actors [31]. Sociotechnical transitions are frequently examined by utilizing a multilevel perspective (MLP). An important analytical benefit of an MLP lies in its capacity to demonstrate how sociotechnical regimes may be disrupted by the emergence of alternative niche technologies and external changes at the broader 'landscape' level. This disruption of the regime can create a window of opportunity, enabling proponents of niche technologies to impact policy-making processes in support of their technology [34–36].

First, an MLP approach recognizes that sociotechnical transitions occur through the interplay of three dimensions: landscape, sociotechnical regimes, and niche. Landscape mainly refers to the long-term trend in sociopolitical and cultural changes at the macro-level; these landscape changes are the force that causes changes in the next dimension, the sociotechnical regime [32]. Sociotechnical regimes consist of the backgrounds, sociotechnical conditions, practices, institutions, and norms in which certain social functions are performed; innovation within these sociotechnical regimes is mostly incremental, aiming at improving rather than disrupting existing technologies. A sociotechnical regime serves as the 'deep structure' ensuring the stability of an existing sociotechnical system [32]. It encompasses a cohesive set of regulations that guide and harmonize the actions of social groups responsible for perpetuating the various components of sociotechnical systems [31]. These established regimes are characterized by a state of inertia, with innovation occurring gradually through minor adjustments that accumulate into established pathways. These pathways extend beyond technological advancements to encompass cultural, political, scientific, market, and industrial dimensions. Although each of these dimensions operates with its own dynamics, governed by distinct sub-regimes, they also interact and evolve in tandem with one another [31]. Finally, niche innovation refers to the space of innovation actors that can bring about breakthroughs in sociotechnical systems. This paradigm of sociotechnical transitions can be described as the process of dismantling an existing sociotechnical regime and constructing a new one by effectively utilizing the window of opportunity created by macro-environmental changes to establish a new sociotechnical system [37].

In this context, the 'window of opportunity' theory is a theory that explains the process by which policy changes or innovative decisions are made, and is used to define the conditions that can lead to change when opportunities arise in a particular context, as well as to interpret the outcomes. The transition of shipping companies to eco-friendly sustainable marine fuels has evolved from a multilayered perspective, with interactions and co-evolution between the components of the layers [38]. In this evolution, a sociotechnical regime is characterized by the intersection of various balances and imbalances of challenges and opportunities, including the relationship between regulators such as the IMO and actors such as shipping companies, in addition to the hardware and software elements involved in ship operations [39]. At this niche stage, we understand sustainable development as part of a process of active adoption through competition or combination with sociotechnical regimes, rather than a shipping company's transition to alternative marine fuels in response to external pressures. Therefore, this study aims to explore the interaction process between sociotechnical regimes and niche innovations regarding sustainable marine fuels with which to interpret the eco-friendly marine fuel shift and its implications. It is based on the 'window of opportunity' theory, which posits that both sociotechnical regimes and niche innovations are influenced by and influence the external environment.

2.2. Method for Analysis

Both the IMO and states recognize the reluctance to adopt new international conventions and technologies as a market failure, and provide incentive policies, such as various subsidies and grace periods, to stimulate the market and rigid policies, such as strict PSC inspections, to improve the situation; however, unilateral policies based solely on these incentives and rigidity have not been very effective in transforming the shipping industry's landscape, which demands a broad spectrum of technological transitions [40]. Therefore, it

is important to comprehensively understand the paradigm shift of the shipping industry through a sociotechnological system that is closely linked to the surrounding factors such as society, technology, environment, and culture.

Therefore, this study attempts to open a window of opportunity based on the multi-level perspective (MLP) approach from the perspective of the shipping industry, as shown in Figure 5 below. The sociotechnical transition paradigm of the sustainable shipping industry in this study expresses the niche innovation process as a window of opportunity with which to change the sociotechnical regime of the shipping industry from various perspectives in order to achieve global decarbonization due to transboundary climate change and transboundary air pollution. In this theoretical framework, the stakeholders of the shipping industry realistically consider how and when to accept the changing regulations in accordance with the macro-environment; it includes a step-by-step consensus with which to minimize the gap in acceptance of the change by deriving niche innovation strategies among the challenges and opportunities [7,31,41,42].

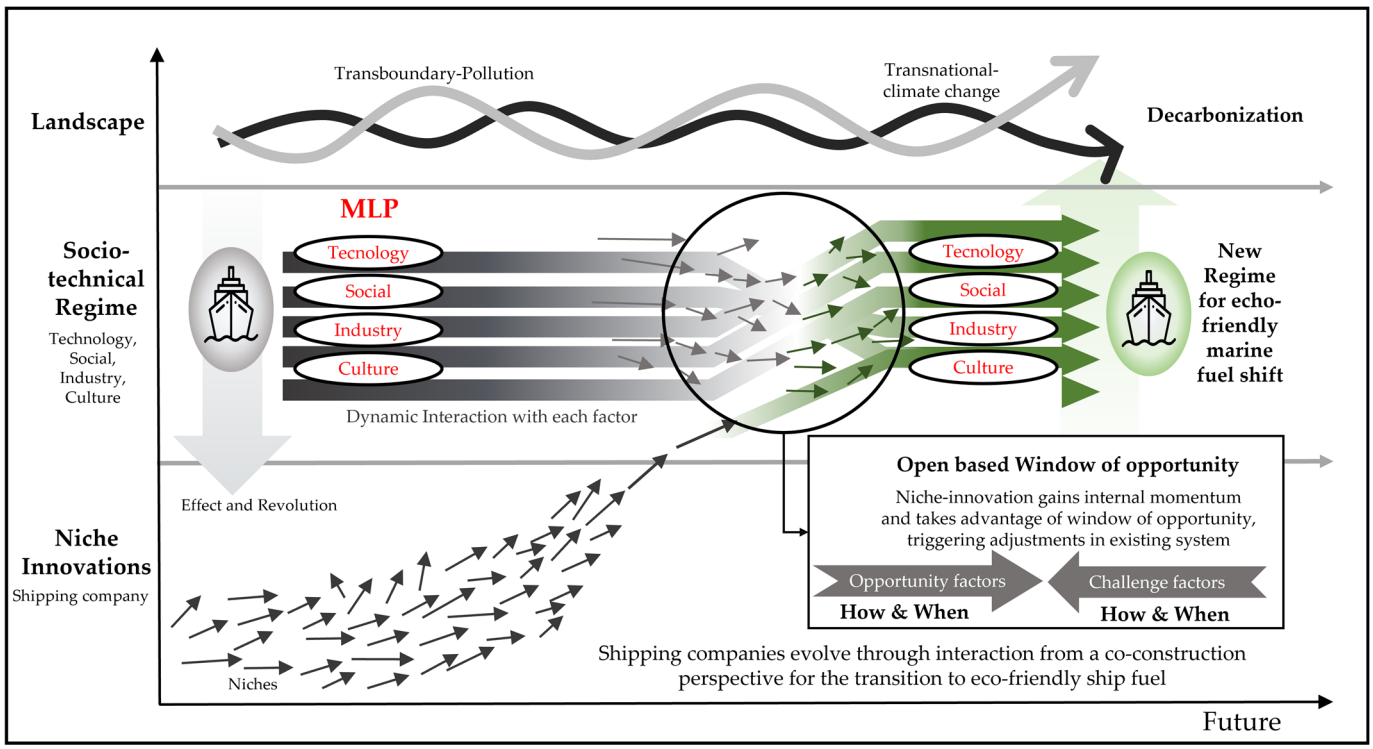

Figure 5. Sociotechnical transition paradigm of the shipping industry toward an eco-friendly marine fuel shift. Source: authors' own modification based on Geels, Comtet, and Johannessen.

3. Empirical Result

3.1. The Challenging Factors in the Shift to Eco-Friendly Marine Fuels

In this section, the study discusses some challenging factors in the shift to eco-friendly marine fuels. **First, from a 'technical' perspective**, ship owners are seeking to comply with the IMO environmental regulations, not only to go after social value but also to ensure sustainability through the pursuit of profit. Therefore, the main challenge from a micro-perspective is that the cost of new buildings for the transition to LNG, methanol, ammonia, and hydrogen fuels increases by 30–40 percent compared to traditional HFO bunker-fueled ships, which increases the burden of capital expenditure (CAPEX) costs. In addition, complex equipment, such as boil-off gas reliquefaction, FGSS, fuel gas bunker tanks, gas combustion units, venting systems, etc., should be installed compared to traditional HFO bunker-fueled ships, requiring maintenance and experienced crew on board [43]. As the laminar burning speed of hydrocarbon-based fuels, such as diesel, LNG, and methanol, is around 40 cm/s, while hydrogen is 200 cm/s and ammonia 10 cm/s, it is necessary

to solve the problem of how fast fuel and air are mixed in order to increase combustion speed by using the high-intensity turbulence generated by the high-pressure injection of ammonia into a combustion chamber in the same way as in existing diesel engines and diesel cycles [44]. Particularly for large shipping companies, with so many alternative ways of converting conventional fuels into eco-friendly marine fuels, it is not surprising that there is a path-dependency problem similar to that of the past. Path-dependent decisions are made to expand the use of very-low-sulfur fuel oil (VLSFO) and desulphurization units [45]. While there is a consensus that LNG, methanol, ammonia, and hydrogen are the most likely future green fuels to replace bunker fuel, most fuels have several issues that need to be resolved before they can be commercialized, including new infrastructure, global productivity, safety, and technical certainty [14]. In addition, South Korea still lacks much of the infrastructure to supply green fuels. For example, the way to supply LNG for marine fuel can be divided into ship-to-ship, truck-to-ship, and pipe-to-ship; however, South Korea still lacks LNG storage tanks and terminals at ports, and, as of January 2024, there are only three LNG bunkering vessels that can directly supply LNG fuel to LNG-fueled ships. Most importantly, LNG bunkering vessels must be able to reduce the time and cost of ship arrivals and departures through SIMOPs (simultaneous operations), where cargo unloading and bunkering take place simultaneously [46]. This transition to eco-friendly marine fuels cannot be left to private shipping companies alone but must be accompanied by the development of eco-friendly marine fuel bunkering infrastructure and legislation at the government level. If such cooperative governance is not possible, the transition to eco-friendly marine fuels will be an obstacle to the development of the industry. As a representative example, HMM, a large Korean shipping company, initially considered ordering LNG-fueled ships in response to the sulfur oxide regulation, but ultimately ordered 20 ships with scrubbers in 2020 [47]. In addition, HMM separately ordered nine 9000 TEU methanol-powered ships in February 2023 in preparation for the competition for capacity and routes among global liner shipping companies when the dissolution of the 2M (Maersk (Copenhagen, Denmark) + MSC (Geneva, Switzerland)) alliance occurred in February 2023 and ocean freight rates plummeted due to the global economic downturn and declining volumes [48]. In this real-life case, even global liner shipping companies face many challenges in establishing a long-term business strategy and transitioning to cleaner marine fuels in the face of excessive competition for vessels.

Second, from a 'social' perspective, the sharp rise in natural gas prices caused by the war between Ukraine and Russia that started in 2022 and the conflict between Israel and Hamas that started in 2023 has also affected the international shipping market, driving up the price of LNG. In response to these changes in the global situation, shipping companies are considering changing their vessel fuel systems to dual-fuel systems that can use LNG, methanol, ammonia, and hydrogen, either alone or in combination, along with traditional bunker-based fuel propulsion [49]. In the long term, shipping companies' green ship fuel transition strategies should be prepared to respond to global political, economic, social, and environmental changes, and allow for a flexible choice of fuels appropriate to the route and type of ship [50]. As of 2023, the Eco-friendly Ship Conversion Support Project, supported by the Korean Ocean Business Corporation (Busan, Republic of Korea) under the Ministry of Oceans and Fisheries, has a fiscal policy to subsidize 10% of the new vessel price for 20-year-old national flag vessels, including bare boat charter hire purchases (BBCHPs) that are to be scrapped or sold (only if sold to a third country); however, the criteria for eligible vessels include both LNG-fueled newbuilding options and scrubber installation options, and the difference in scores is small [51]. Therefore, this fiscal policy is not an attractive incentive for shipping companies to actively promote the transition to eco-friendly marine fuels.

Third, from an 'industrial environment' perspective, small shipping companies cite the increasing maintenance costs of managing their shipping fleets in response to internal and external demands for green marine fuel conversion as the biggest challenge. As mentioned above, compared to large shipping companies such as HMM, small shipping

companies are at a comparative disadvantage in terms of their ability to develop their own green marine fuel bunkering infrastructure, networking, and contractual arrangements, which limits their ability to transition to the use of eco-friendly marine fuels. Despite the need to attract quality seafarers by offering high wages, benefits, and training, the reality is that wages are relatively low compared to those of large shipping companies, which limits their ability to build or charter new ships and operate ships powered by green fuels such as LNG, methanol, ammonia, and hydrogen. Smaller shipping companies face many challenges in adopting cutting-edge technologies, such as fuel switching, due to their small size and inability to operate all of the departments required to manage a single vessel, such as operations, public affairs, human resources, health and safety, and financial accounting [52]. For example, a typical LNG-fueled vessel requires qualified and experienced seafarers, as it has additional facilities, such as on-deck LNG storage tanks, gas supply and combustion package units, and safety systems, compared to conventional vessels. However, it is difficult to gather and train a lot of seafarers as there is a shortage of qualified seafarers to work on LNG carriers both domestically and internationally. Finally, while most small shipping companies agree with the conceptual review of green fuel ships, there are economic and technical limitations to building and operating new types of green fuel ships because of the strengthening of regulations by the IMO on the way forward, as well as the financial support policies of the government. In particular, small shipping companies are not strongly encouraged by big shippers to include the use of green fuels in their charter contracts from an ESG perspective, which limits their ability to voluntarily operate ships with high additional ship management costs [53]. This is because small shipping companies are highly sensitive to fluctuations in the price of green marine fuels. In particular, small shipping companies have a relatively small fleet compared to large shipping companies, which makes it difficult for them to obtain volume discounts for large quantities of green marine fuels such as LNG, methanol, ammonia, and hydrogen, all of which are imported in South Korea [54].

Fourth, from an ESG-based 'corporate culture' perspective, the issue of sustainability in the shipping industry has been raised as a key issue for major stakeholders, such as shippers, shipyards, shipping companies, port authorities, etc., due to the increasingly serious problem of air pollution from ships. In particular, the reason that sustainable technologies related to eco-friendly ships have not been installed on ships or applied to new ships as quickly as the IMO had hoped is that shipyards and ship owners have to invest large amounts of money and bear high uncertainty as well as risk [55]. These challenges have resulted in high prices in the shipbuilding and chartering markets, which have discouraged charterers and shippers from actively choosing eco-friendly ships [56]. The conservative culture of the shipping industry is a significant challenge to ESG-based corporate culture changes. Therefore, shipping companies still prefer to use conventional HFO fuel propulsion, and resistance to new green marine fuel technologies poses a challenge to the innovation and development of an eco-centric corporate culture based on ESG principles.

3.2. The Opportunities for the Shift to Eco-Friendly Marine Fuels

Aiming to achieve zero emissions across its operations and product range by 2040, AP Moller—Maersk has signed an agreement with the Chinese clean energy company Goldwind to supply 500,000 tons of green methanol per year from 2026. At the same time, Maersk ordered a new fleet of 172 m, 2100 TEU, and twin-engine container ships that can run on methanol or traditional ultra-low-sulfur fuels, and has committed to carrying 25 percent of all seaborne cargo on green-fueled vessels. In response to Maersk's efforts, global shippers have expressed positive support for Maersk's green policies, and most of them are optimistic about the long-term mutual benefits and increased competitiveness of the shipping market [57]. It is worth exploring the emerging opportunities in this situation so that shipping companies can play an important role in effectively implementing the transition to green marine fuels and achieving long-term environmental goals through

policy support from governments and win–win governance between ship owners and shippers.

In this section, the study discusses some opportunity factors in the shift to eco-friendly marine fuels. **First, from a 'technical' perspective**, there is a tendency to focus on large ships and medium-sized container ships in the domestic shipping industry; indeed, 79% of the new ship orders of domestic shipping companies in the past three years in terms of the number of ships are for large container ships [58]. Hence, the new ship orders of small- and medium-sized shipping companies, other than container ships, are still insufficient. In addition to the technical uncertainties, it is necessary to prepare new opportunity factors for the problem of insufficient financial resources [58]. Opportunities from both technical and economic perspectives can play an important role in the shipping industry's transition to green marine fuels. Furthermore, governments and industry need to support shipping companies to actively exploit these opportunities to enhance their sustainable and green competitiveness [59]. This includes long-term R&D of new technologies and the construction of multi-test bed ships to remove technical uncertainties to encourage shipping companies to participate. Shipping companies should take advantage of these opportunities by applying new technologies that have been verified on existing ships gradually, and by returning relevant maritime data to researchers after demonstration to enhance the opportunities [60].

Second, from a 'social' perspective, the government must introduce long-term incentive policies to mitigate financial risks, such as high shipping and maintenance costs, for shipping companies arising from the transition to green ship fuels, by extending the duration of the contract of affreightment (COA) promoted by energy utilities, such as the Korea Gas Corporation (Daegu, Republic of Korea), Korea National Oil Corporation (Ulsan, Republic of Korea), and Korea Electric Power Corporation (Naju-si, Republic of Korea), from 3–5 years to 5–10 years [61]. In addition, there is a need for a track record and government guarantee for coastal routes in which small shipping companies can participate. First, governments and shippers should actively participate in discussions on the revision of the IGF Code (International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels) and the IMO safety standard for LNG-fueled ships, to help small- and medium-sized shipping companies meet the IMO safety standards. Efforts should also be made to maintain governance through public–private partnerships (governments, classification societies, universities, companies, etc.). Second, track records are particularly important when applying unfamiliar technologies to ships. An example is the support for high-manganese steel, a new material for LNG fuel tanks developed by a domestic company (POSCO), to be included in the IMO safety standard (IGF Code). In addition, efforts have been made to establish a truck-to-ship (TTS) LNG bunkering system [62], including the installation of LNG facilities, for the smooth operation of the 'Green Iris' at Donghae Port. The Green Iris is a 50,000 dwt bulk carrier operating on the Donghae–Kwangyang route.

Third, from an 'industrial environmental' perspective, extending the duration of long-term contracts of affreightment (COA) can help shipping companies mitigate the burden of higher freight rates and maintenance costs associated with switching to cleaner marine fuels, while ensuring stable revenues over a longer period, enabling long-term business planning and building trusted partnerships from a shared governance angle between ship owners and shippers [63]. This virtuous cycle allows shipping companies to secure the time and resources needed to respond to various environmental regulations and invest in green technologies of the IMO to meet carbon emission reduction targets. In addition, it enhances their competitiveness in the global shipping market and seizes the opportunity to contribute to promoting green technology innovation and development [64]. Therefore, the government should diversify the monopoly on LNG supply in the Korea Gas Corporation to ensure price competitiveness and expand opportunities for shipping companies to promote the transition to green marine fuels by sustaining LNG prices in the green fuel market at reasonable levels.

Fourth, from an ESG-based 'corporate culture' perspective, shipping companies need to go through the steps of transitioning to eco-friendly fuels to realize their ESG goals by establishing a green corporate identity and adopting behaviors that meet global standards for a sustainable marine environment. Korean shipping companies should have an attitude to transfer their values towards sustainability within their corporate cultures for the transition to green marine fuels. This transition will act as an opportunity for the development and implementation of internal policies that encourage shipping companies to adopt behaviors that are in line with global standards for protecting a sustainable marine environment and promote conscious efforts towards green innovation among onshore and offshore employees [65]. Therefore, expanding ESG-principle-based practices will play a key role in helping Korean shipping companies successfully achieve the transition to green marine fuels, which will contribute to enhancing their brand value and market competitiveness in the long run.

3.3. Innovative Strategy to Integrate the Opportunities and Challenges for Shifting to Eco-Friendly Marine Fuels

This study examines the challenges and opportunities that negatively impact the innovation activities of shipping companies and the strategic implications for a sociotechnical system shift towards an eco-friendly shipping industry. Figure 6 shows the synthesis results of the niche innovations strategy. During this shift in the shipping industry, we need to consider which strategic niche innovations can lead to decarbonization. We need to overcome the challenges identified above and strengthen the opportunities to successfully make an eco-friendly shipping industry; niche innovations will provide strategic opportunities with which to overcome these challenges and move towards in a new direction. Our proposed niche innovation strategy is as follows:

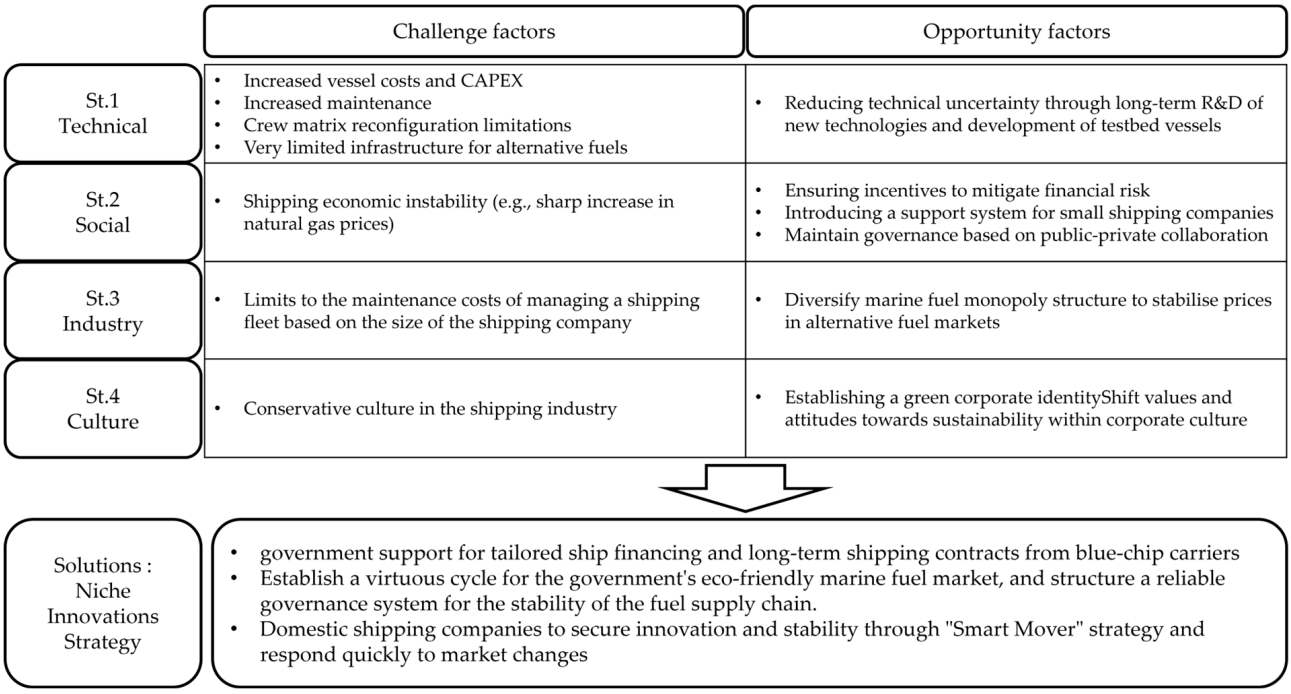

Figure 6. Finding solutions: niche innovation strategies that integrate opportunities and challenges.

First, even though shipping companies have experienced a short-term decline in freight rates due to COVID-19 and the Ukraine–Russia as well as Israel–Hamas wars, they have pursued risk management based on route maintenance strategies rather than strategic investments. This 'low-cost, high-efficiency ship operation strategy' is a key challenge to the 'green ship fuel transition', which requires high production and maintenance costs. Therefore, the government should expand support for ship financing tailored to the size

of the company to help shipping companies overcome the challenges that they face. In addition, domestic big shippers should make long-term shipping contracts with shipping companies on a FOB (free on board) basis to induce shipbuilding based on the green ship fuel transition.

Second, suppliers of LNG, methanol, ammonia, and hydrogen fuels would like to reduce transaction uncertainty through long-term purchase contracts of 10–15 years with creditworthy buyers to ensure the stable recovery of large capital investments. In addition, the high cost of LNG, methanol, ammonia, and hydrogen fuels due to the monopolistic supply structure of LNG, methanol, ammonia, and hydrogen fuels, as well as the lack of infrastructure, are key challenges for shipping companies to adopt green marine fuels. These social environments have led to a lack of certainty among shipping companies as to whether LNG, methanol, ammonia, or hydrogen fuel is the right choice in the short, medium, or long term. In order to overcome the structure of shifting responsibility to each other, it is necessary to establish a governance system to stabilize the fuel supply chain between suppliers and consumers of green marine fuels, with the participation of the Ministry of Oceans and Fisheries, to create a virtuous cycle of the green marine fuel market, and to establish a system of the mutual verification of reliability.

Third, shipping companies have traditionally been route-dependent and conservative, which has led to a non-innovative attitude towards the transition to green marine fuels. This passive embrace of the transition could ultimately undermine the global competitiveness of shipping companies. The reality is that the passive technology adoption strategy of small- and medium-sized shipping companies, fueled by the fear that their inability to close the technology gap within a given timeframe, could boomerang into a financial risk factor in the future. Therefore, it is very important for small- and medium-sized shipping companies to strategically promote their willingness to share investment risks with large shipping companies in order to close the technology gap. To overcome this, domestic shipping companies should move away from their current conservative attitude and promote investment as well as innovation in new environmental technologies. Then, they should ensure financial stability and respond quickly to market changes. In particular, the 'first mover' strategy, centered on large shipping enterprises, should be replaced by a 'smart mover' strategy, based on the trickle-down effect centered on small- and medium-sized shipping companies.

4. Discussion

The world is already talking about the need for systemic transformation at multiple levels, including green technologies, new infrastructure, user practices, policies, and culture, to combat transnational air pollution and climate change [4–6]. In agreement with them, we have sought to identify breakthroughs in the shipping industry from various aspects of the sociotechnical system (technology, politics, culture, industrial environment, and infrastructure) for green innovation. In the long term, such as the IMO's 2050 net-zero goal, the shipping industry essentially needs to be sustainably greened. Nevertheless, the focus is still on technical fuel conversion [13–21], and we need to go further.

Our aims were to provide a forward-looking analysis of the paradigm shift amidst multiple uncertainties, considering longer-term perspectives, such as the IMO's goal of achieving net-zero emissions by 2050. Additionally, we utilized the window of opportunity theory within the sociotechnical transition framework to gain deeper insights into the transition from traditional bunker fuel systems to eco-friendly sustainable fuel systems in the shipping industry. The analysis explored the potential impact of this approach on shipping companies as innovators in reducing GHG emissions.

Shipping companies regard their ships as critical assets with a long service life, so they tend to prioritize proven empirical data and minimize risk; however, it is essential to make the transition because of the global climate change crisis. From this perspective, this study proposed that ordering LNG-, methanol-, ammonia-, and hydrogen-fueled vessels was a suitable 'window of opportunity' with which to interpret the sociotechnical regime

transition in the maritime sector as a way for domestic shipping companies to strengthen their ESG-based shipping competitiveness for the IMO 2020 sulfur oxide regulation and carbon neutrality. The challenges and opportunities accompanying the niche stream in the multilevel interaction process were analyzed separately, and directions for the improvement of niche strategies were suggested. Our findings are presented below.

First, the challenge factors of the innovation process for the shipping industry included high ship prices, CAPEX costs, strengthening maintenance, limited crew matrix reconfiguration, and a severe lack of infrastructure for alternative marine fuels from a technical perspective, while it was identified that instability in the shipping economy, such as from the sharp rise in natural gas prices, was the challenge from a social perspective. This said, there is a limit to the maintenance costs required to manage a shipping fleet based on the size of shipping companies from an industry perspective. Last, in terms of a corporate culture perspective, there was the conservative structure of the shipping industry.

Second, the opportunity factors of the innovation process for the shipping industry included the resolution of technical uncertainties through the long-term R&D of new technologies and the development of test bed ships. From a social perspective, it included the government's introduction of incentive policies to mitigate financial risks, the introduction of a support system for small shipping companies, and the maintenance of governance based on public–private collaboration. Then, from an industry perspective, it included diversifying the fuel monopoly structure to stabilize prices in the alternative marine fuel market. Last, from a corporate culture perspective, it was clarified that the main opportunities were establishing a green corporate identity and shifting values and attitudes towards sustainability within the corporate culture.

Finally, in the face of these challenges and opportunities, the study uncovered some niche innovation strategies that could lead to a revolutionary transformation. First of all, government support for tailored ship financing and long-term shipping contracts from blue-chip carriers should be made. Second, a virtuous cycle needs to be established for the government's eco-friendly marine fuel market, and a reliable governance system for the stability of the fuel supply chain needs to be structured. Last, domestic shipping companies should ensure financial stability and respond quickly to market changes as smart movers.

The reality for domestic shipping companies, as discussed above, is that they are at imminent risk of losing their competitiveness in the shipping market in the near future due to stricter global regulations on eco-friendly marine fuels and ESG practices for shipping companies, which may result in fines or disadvantages for their shipping operations if they fail to comply with these regulations. Therefore, the government should support shipping companies with strategies to respond to these possibilities promptly. In addition, it is necessary for shipping companies, even if they are not necessarily leaders in the shipping market, to develop a strategy to act as 'smart movers' that can respond to the rapidly changing market environment with a focus on 'greening'.

However, merely having such a direction makes it difficult to obtain substantial execution power. So, for the commercialization of eco-friendly fuels in the maritime industry, collaboration and cooperation among various stakeholders such as the Shipowners' Association, the Seafarers Union, the government, the Shipping Company, and the Maritime Education Institute within the maritime industry are essential. To achieve this, it will be necessary to solidify a joint decision-making governance within the maritime industry through the establishment of a 'Green Shipping Initiative', in order to progressively achieve the IMO 2050 goals and ensure execution power, while enhancing the functionality of communication. Ultimately, these efforts will play a crucial role in exploring the sustainable future of the maritime industry. The proposed strategic pathways and components of the initiative we aim to present are as shown in Figure 7 below.

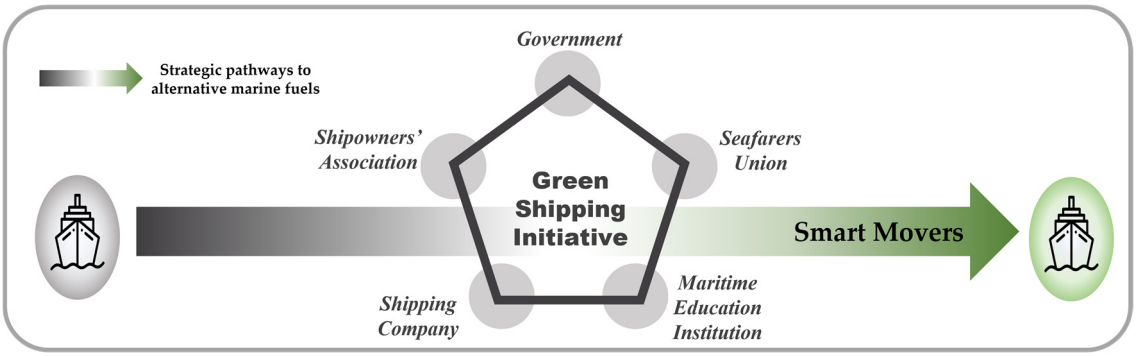

Figure 7. Green Shipping Initiative for the transition to green marine fuels in the shipping industry.

5. Conclusions

We proposed a gap-filling strategy for the eco-friendly marine fuel shift, employing a sociotechnical system transformation approach to enhance contextual understanding and foster niche innovation. This study critically analyzed the transition process of the Korean shipping industry to eco-friendly marine fuels, such as LNG, methanol, ammonia, and hydrogen, through a sociotechnical system approach. By applying the 'window of opportunity' model of sociotechnical system transition theory, this study contributes to a detailed understanding of the dynamic interactions between different stakeholders in the transition to eco-friendly fuels. In particular, the interpretation of qualitative data based on a literature review effectively highlights the challenges and opportunities associated with the transition from traditional bunker fuels to eco-friendly sustainable fuel systems. This study has identified the challenges and opportunities that may arise in the process of moving towards an eco-friendly paradigm shift in the shipping industry, and identified niche strategies that shipping companies can strategically pursue. Consequently, even for shipping firms not at the forefront of the market, it is vital to devise a plan to function as a 'smart mover' capable of adapting to the swiftly evolving market dynamics, particularly with an emphasis on environmental sustainability. It will be essential to establish a Green Shipping Initiative among stakeholders in the shipping industry to commercialize green marine fuels in line with our proposed direction. They are expected to play a key role in charting a sustainable future for the shipping industry.

The transition in these sociotechnical systems suggests a gradual and incremental approach in various aspects rather than a radical paradigm shift; therefore, this study provides an important contribution to understanding the complexity and multifaceted interactions involved in the shipping industry's transition to eco-friendly fuels, highlighting the roles of policy, technology, and markets, and identifying the factors needed to facilitate this transition. As a suggestion, it is important to recognize that this study focused primarily on the Korean context, which may limit its applicability to other regions. In addition, relying solely on literature review data may not yield empirical findings and may introduce bias. To address these limitations and increase the robustness of future research, it is advisable to conduct studies in different regional contexts. By considering the specifics of the shipping industry in different regions, researchers can gain insights into global patterns and better understand the long-term economic and environmental impacts of different green fuels. In addition, future studies should explore how international cooperation and the development of policy frameworks can better support the green transition of the shipping industry. This would contribute to a broader understanding of sustainable practices and policies in the maritime sector.

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