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Jeongmin Lee , Minseop Sim , Yulseong Kim , Changhee Lee *

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Strategic Pathways to Decarbonization: Socio-Technical System Innovations for Green Shipping Compliance with IMO 2050 Targets

Jeongmin Lee [1], Minseop Sim [1], Yulseong Kim [2] and Changhee Lee [3,*]

[1] Department of Convergence Interdisciplinary Education of Maritime & Ocean Contents (Logistics System), Korea Maritime and Ocean University, Busan 49112, Korea; jmjm3646@g.kmou.ac.kr(J.M.) ; tla6355@g.kmou.ac.kr(M.S.)

[2] Department of Logistics, College of Engineering, Korea Maritime and Ocean University, Busan 49112, Korea; logikys@kmou.ac.kr(Y.K.)

[3] Division of Navigation Convergence Studies, College of Maritime Sciences, Korea Maritime and Ocean University, Busan 49112, Korea; chlee@kmou.ac.kr(C.L.)

* Correspondence: chlee@kmou.ac.kr; Tel.: +82-010-8577-8618 or +82-051-410-4642; Fax: +82-051-404-3985

Abstract: This study investigates the transition to sustainable shipping industry within the framework of the IMO's 2050 carbon neutrality objective, focusing on socio-technical systems analysis. The research delves into the sustainable paradigm shift towards alternative marine fuels such as LNG, methanol, ammonia, and hydrogen from a socio-technical transition perspective, analyzing the multi-level 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 existing literature on ship emissions and alternative fuels, coupled with socio-technical transition theory, the 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; Socio-technical systems analysis; sustainable future

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. And 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 sulphur oxides (SOx) and nitrogen oxides (NOx) 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 fir st 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 on the reduction of GHG emissions from ships, setting a target of a 50% reduction in GHG emissions from international shipping by 2050 (compared to 2008 levels). And, at the 80th session of the Marine Environment Protection Committee (MEPC) in 2023, the IMO adopted the '2023 IMO GHG Strategy',

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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 modification, adjusting course navigation, and scrapping of old ships. These measures are aimed at achieving ESG management within shipping companies by reducing the emission of sulphur 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-sulphur 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].

1.2. Aims

According to the '2023 IMO Strategy,' the IMO sulfur oxide emission regulation necessitates a paradigm shift to enhance competitiveness by transitioning from the current HFO-based bunker C to eco-friendly sustainable marine fuels such as LNG, methanol, ammonia, and hydrogen. Despite this paradigm shift offering a new opportunity for Korean shipping companies, this study was initiated to explore whether Korean shipping companies are taking a proactive stance in transitioning to sustainable marine fuels. From the perspective of the socio-technical system of the shipping industry, it is evident that significant academic research is needed to drive this paradigm shift. This shift is driven by a confluence of various factors, including political, economic, and technological changes, involving domestic and international institutions, stakeholders, and the maritime industry. Therefore, this study aims to assess the effectiveness and limitations of transitioning to a sustainable shipping industry from a problem-solving perspective. It draws upon theories of air pollution regulation grounded in transnationality and transcendence, socio-technical system transformation theory, and the window of opportunity theory. In essence, this study aims to identify the challenges and opportunities in the process of transitioning to sustainable marine fuels within the shipping industry, with the aim of guiding future adoption. The study proposes a gap-filling strategy for the eco-friendly marine fuel shift, employing a socio-technical system transformation approach to enhance contextual understanding and foster niche innovation.

1.3. Literature Review

GHG emissions from ships continue to rise, 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 NOx and SOx 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 IMO Strategy on reduction of 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 2008 levels; reducing annual GHG emissions from international shipping by at least 70% by 2040, aiming for 80%, compared to 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 a 10% effort) of total international shipping energy to zero or near-zero technologies and fuels by 2030. This strategy appears to directly regulate to achieve the 2050 net-zero target, and it is likely that the 2030 target will be strengthened by the IMO's forthcoming medium-term measures for GHG reduction and the marine fuel standard regime [4].

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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 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, updated SEEMP, and the Carbon Intensity Index (CII), are still under negotiation, and the effectiveness of these measures is yet to be determined [5]. 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 emission characteristics [6]. 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 [7]. 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 [8]. Concurrently, alternative marine fuels are being adopted and utilized as crucial solutions to mitigate ship-related air pollutants, and research on these alternative marine fuels by international organizations such as the IMO is growing and becoming increasingly important [9]. In this context of increasing interest and importance of alternative marine fuels, Hansson et al. (2019); Deniz et al. (2016); Chiong et al. (2021); Elgohary (2015); and many researchers 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 [10],[11],[12],[13].

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 most suitable for each sector of the shipping industry in the near and long term [14]. 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 [7].

Previous studies on GHG emissions from ships have aimed to tackle the environmental challenges facing the shipping industry by exploring the use of alternative marine fuels. Most of these studies have primarily focused on the technical aspects of fuel switching. While these studies 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. Therefore, this study aimed 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 zero net emissions by 2050. To achieve this, the study explores comprehensive strategies and measures 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.

1.4. Research Approch

The introduction of alternative marine fuels into the shipping industry, despite a range of social support and technological efforts, still faces many challenges, marking a critical juncture in the transition to a sustainable shipping industry. The sustainable shipping industry needs to be considered from a broad and multi-faceted perspective, including not only technical aspects but also social systems. The socio-technical systems perspective argues that national and international institutions, stakeholders, and the shipping industry interact across various domains of political, economic, and technological change. This perspective posits that the combination of these factors leads to an overall paradigm shift. In other words, government policies and regulations, technological innovations, and changes in the industrial environment and culture interact to produce changes in the entire socio-technical system. In this situation, as a first step in the research approach, an examination of the current state of the literature on the sustainable shipping industry can provide insights into the overall status and changes of the socio-technical system. For this purpose, a total of 509 high-quality articles on Web of Science were collected using the keywords 'shipping + GHG + emission' from 1 January 2008 to 31 December 2023. The collected data was combined with the emergence of IMO environmental regulations and strategies. The first period was selected as 2008, the baseline year of IMO environmental regulations, and 2013, when direct air pollution reduction regulations EEDI and SEEMP were implemented. The second period was selected as 2014 to 2018, when the initial IMO strategy was established. The third period was selected as 2019 to 2023, when the IMO 2023 strategy was recently announced. Figure 1 shows the results.

Type	Survey Year	Survey Media	Total (unit : ea)
High-quality article	2008-2023	Web of Science	509

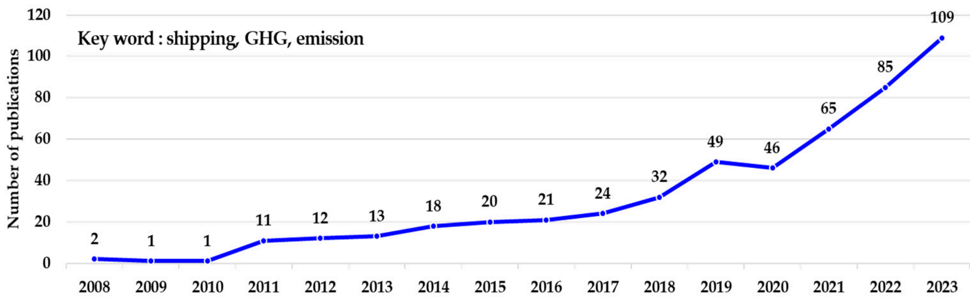

Figure 1. Trends in the publication of WOS articles on GHG emissions in the shipping industry (2008-2023).

Next, based on the previously collected WoS studies, the period from 2008 to 2023 was divided into the core years of IMO environmental regulations, and an ego-network analysis was performed using Netminer 4.5, focusing on "marine fuel". The result is shown in Figure 2. Here the nodes are colored as follows: grey for general words, black for conventional marine fuels (fossil fuel, HFO, etc.), blue for alternative marine fuels (biofuel, ammonia, methane, LNG, etc.), green for technical measures to reduce GHG emissions, and the size reflects the frequency, and the thickness of the link also indicates the number of connections. Upon analyzing trends in the publication of WOS articles on GHG emissions in the shipping industry, distinct patterns emerge across different periods. In the first period (2008-2013), the focus was primarily on fossil fuels. During the second period (2014-2018), 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. Since 2008, there has been an ongoing transition from reliance on predominantly fossil fuels to eco-friendly sustainable marine fuels, coinciding with the inception of environmental regulations. Research activities in this area have been robust. However, based on the previous research review and ego-network analysis, the research trends related to GHG emissions from ships have mainly focused on technical aspects such as types of alternative marine fuels, applicability and efficiency, and related infrastructure requirements for reducing GHG emissions from ships, and the sustainable paradigm shift in the shipping industry is still unknown from various perspectives. This study aims to effectively highlight the challenges and opportunities inherent in the socio-technical transitions theory. By considering and addressing potential blind spots from a multifaceted perspective, the study seeks to facilitate a sustainable paradigm shift in the shipping industry. Additionally, it utilizes the window of opportunity theory within the socio-technical transitions framework to gain deeper insights into the transition from traditional bunker fuel systems to eco-friendly sustainable fuel

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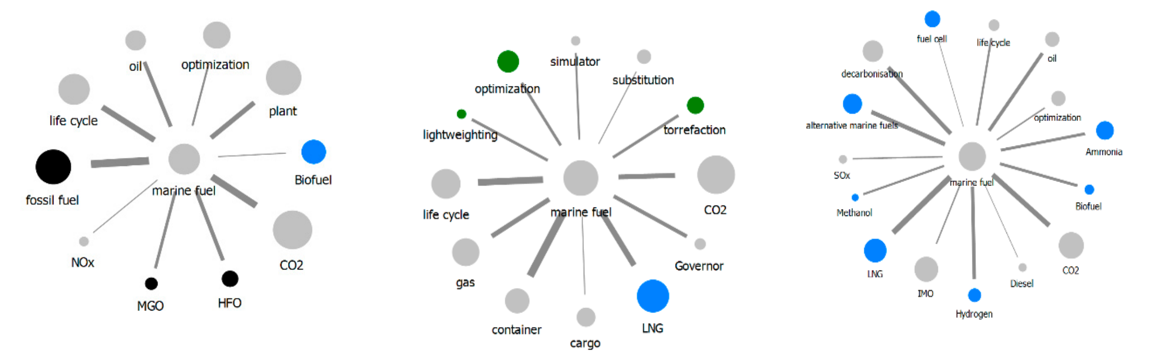
systems in the shipping industry. The analysis explores the potential impact of this approach on shipping companies as innovators in reducing GHG emissions. By addressing this gap in the existing literature, the study contributes significantly to the multifaceted discussion on decarbonizing ship-based air pollution.

1st Period(2008-2013)	2nd Period(2014-2018)	3rd Period(2019-2023)



[Legend] Network : linked line ; Keyword : marine fuel ; Node size : Frequency

Figure 2. Result of Ego-network of WOS Articles focusing on “Marine Fuel” over time.

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, socio-technical, and managerial risks, seizing opportunities for a sustainable future, and enhancing their market competitiveness [15]. 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 [16]. 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 [17]. Furthermore, by minimizing the impact of the 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

From a time series perspective, humanity 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 mass production and sales of automobiles, attention expanded to air pollution [18]. 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 was 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

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Transboundary movements of Hazardous Wastes in 1992, and the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 [19]. 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 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 [20].

2.1.3. Theory of windows of opportunity and innovation for firms in socio-technical transitions theory

The socio-technical transitions theory argues for a transition to sustainable systems, which means that the current socio-technical system is problematic at the system level and that responding to it by improving the existing system will not solve the problem and will lead to difficult situations. Therefore, a multilayered approach to socio-technical transitions considers both macro and micro aspects simultaneously. The multilayered approach recognizes that socio-technical transitions occur through the interaction of three dimensions: landscape, socio-technical regimes, and niche. In other words, as new socio-technical niches emerge, effectively capitalizing on windows of opportunity opened by landscape (macro-environmental changes), transitions can occur, disrupting and replacing existing socio-technical regimes [21]. The landscape (macro-environment) mainly refers to the long-term trend of socio-political and cultural changes at the macro-level, and these landscape changes are the force that causes changes in the next dimension, the socio-technical regime. The socio-technical regime consists of the backgrounds, socio-technical conditions, practices, institutions and norms in which certain social functions are performed, and innovation within this socio-technical regime is mostly incremental, aiming at improving rather than disrupting existing technologies. Finally, niche innovation refers to the space of innovation actors that can bring about breakthroughs in socio-technical systems. This paradigm of socio-technical transitions can be described as the process of dismantling the existing socio-technical regime and constructing a new one by effectively utilizing the window of opportunity created by macro-environmental changes to establish a new socio-technical system [22].

In this context, 'window of opportunity' theory is a theory that explains the process by which policy change or innovative decisions are made, and is used to define the conditions that can lead to change when opportunities arise in a particular context, and to interpret the outcomes. The transition of shipping companies to eco-friendly sustainable marine fuels has evolved from a multi-layered perspective, with interactions and co-evolution between the components of the layers [23]. In this evolution, the socio-technical regime is characterised 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, and the hardware and software elements involved in ship operations [24]. At this niche stage, we understand sustainable development as part of a process of active adoption through competition or combination with socio-technical 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 socio-technical regimes and niche innovations regarding sustainable marine fuels to interpret the eco-friendly marine fuel shift and its implications. It is based on the 'window of opportunity' theory, which posits that both socio-technical 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 new technologies as a market failure and provide incentive policy 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 [25]. Therefore, it is important to comprehensively understand the paradigm shift of the shipping industry through a socio-technological system that is closely linked to the surrounding factors such as society, technology, environment and culture. Merchant ships are engaged in international voyages, so it is necessary to develop not only the physical form of the ship, but also the social factors such as international norms, interest groups, and political, economic, and social forces [26].

Therefore, this study aims to open a window of opportunity based on the multi-level perspective (MLP) approach of socio-technical transitions theory by considering the char-acteristics of ships with a long life cycle from the perspective of the shipping industry, as illustrated in Figure 3 below. The multi-level perspective (MLP) approach based on socio-technical transitions theory was selected for this study because it has the advantage of considering the transition to eco-friendly marine fuel shifts simultaneously for each component by dividing it into the layers of landscape-socio technical regime-niche. Furthermore, the socio-technical transitions paradigm of the sustainable shipping industry in this study expresses the niche innovation process as a window of opportunity to change the socio-technical 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 paradigm, the stakeholders of the shipping industry realistically consider how and when to accept the changing regulations in accordance with the macro environment, and it includes a step-by-step consensus to minimize the gap in acceptance of the change by deriving niche innovation strategies among the challenges and opportunities [27],[28],[29].

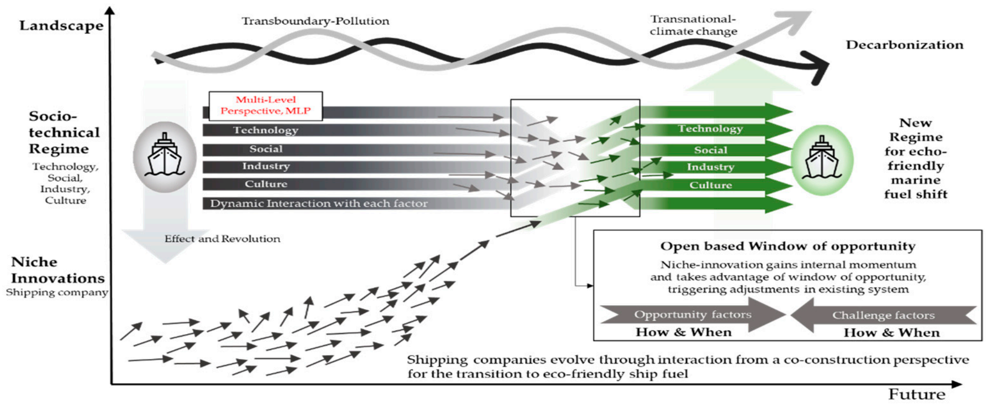

Figure 3. Socio-technical transitions paradigm of the shipping industry toward eco-friendly marine fuel shift.

2.3. Research design and Question

Research into various alternative marine fuels is being actively pursued in line with the IMO's aggressive environmental regulations. This indicates 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 and introduction of new alternative marine fuels is 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 4 shows the time series of IMO environmental regulations and research trends related to GHG emissions from ships. Despite the positive trend towards a new direction of research on the socio-technical transitions paradigm, uncertainties persist in 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 to tackle 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 4 visualizes the Socio-technical Transitions paradigm, which guides the research questions of this study.

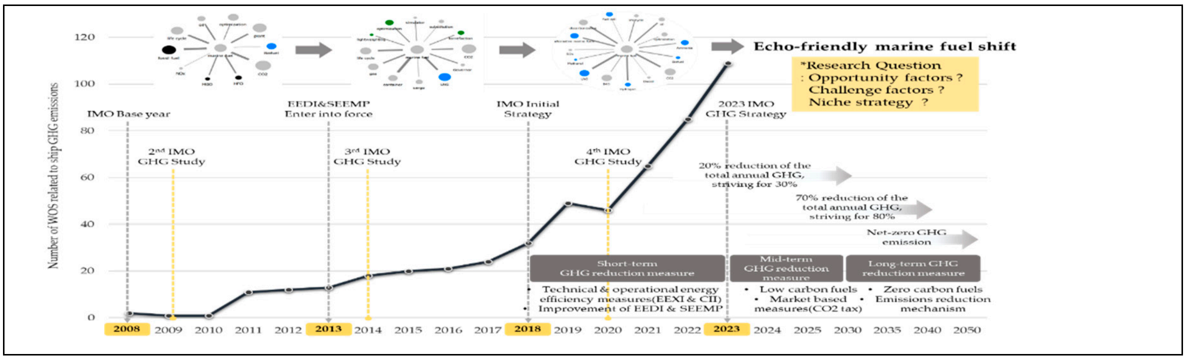

Figure 4. Research design and Question.

Thus, the research questions are as follows:

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 aims to provide a direction for the eco-friendly marine fuel shift in the shipping industry through the actual interaction and contextual understanding of the stakeholders of Korean shipping companies so that the global shipping industry can make timely responses to the future eco-friendly sustainable marine fuel shift paradigm. The flow chart of this research is shown in Figure 5.

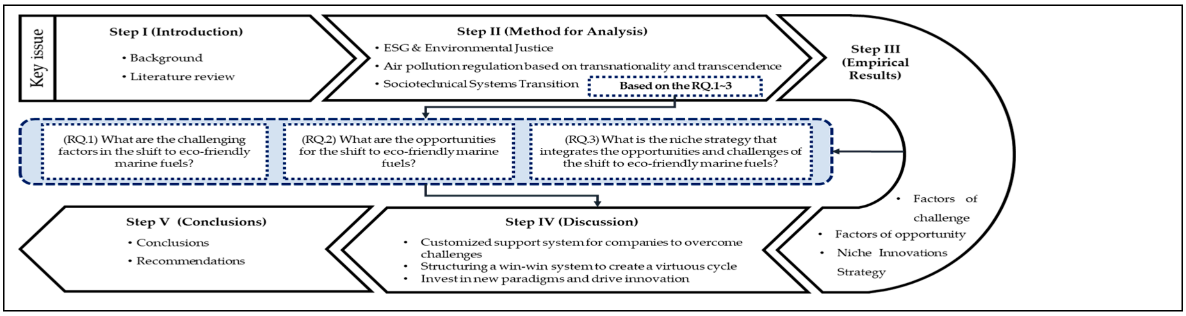

Figure 5. Research flow.

3. Empirical Result

3.1. What are the challenging factors in the shift to eco-friendly marine fuels?

In this section, the study derives some challenging factors in the shift to eco-friendly marine fuels. First, from a "technical" perspective, shipowners are seeking to comply with 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 to convert to LNG, methanol, ammonia, and hydrogen fuels increases by 30 to 40 percent compared to traditional HFO bunker-fuelled ships, which increases the burden of Capital expenditure (CAPEX) costs. In addition, complex equipment such as boil-off gas reliquefaction, FGSS, fuel gas bunker tank, gas combustion unit, venting system, etc. should be installed compared to traditional HFO bunker-fuelled ships, requiring maintenance and experienced crew on board [30]. 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 the fuel and air are mixed to increase the combustion speed by using high-intensity turbulence generated by high-pressure injection of ammonia into the combustion chamber in the same way as in the existing diesel engine and diesel cycle [31]. Particularly for large shipping companies, with so many alternative ways of converting conventional fuels to eco-friendly marine fuels, it is not surprising that there is a path dependency problem similar to that of the past. Pathdependent decisions to expand the use of very low sulfur fuel oil (VLSFO) and desulphurisation units [32]. 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 [7]. 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-fuelled 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 [33]. 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-fuelled ships in response to the sulphur oxide regulation but ultimately ordered 20 ships with scrubbers in 2020 [34]. In addition, HMM separately ordered nine 9,000 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 + MSC) alliance occurred in February 2023 and ocean freight rates plummeted due to the global economic downturn and declining volumes [35]. 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 in 2022 and the conflict between Israel and Hamas 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 system to a dual-fuel system that can use LNG, methanol, ammonia and hydrogen, either alone or in combination, along with the traditional bunker-based fuel propulsion [36]. 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 [37]. As of 2023, the Eco-friendly Ship Conversion Support Project, supported by the Korean Ocean Business Corporation under the Ministry of Oceans and Fisheries, has a fiscal policy to subsidize 10% of the new vessel price for 20 years old national flag vessels including Bare boat charter hire purchase(BBCHPs) that are to be scrapped or sold (only if sold to a third country), but the criteria for eligible vessels include both LNG-fuelled newbuilding options and scrubber installation options, and the difference in scores is small [38]. 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 convert 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 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 the departments required to manage a single vessel, such as operations, public affairs, human resources, health and safety, and financial accounting [39]. 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, and 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 [40]. 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 [41].

Forth, from the perspective of “corporate culture” for ESG practices, 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 ship. In particular, the reason 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 shipowners have to invest large amounts of money and bear high uncertainty and risk [42]. 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 [43]. The conservative culture of the shipping industry is a significant challenge to ESG-based corporate culture change. 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. What are 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 Chinese clean energy company Goldwind to supply 500,000 tonnes of green methanol per year from 2026. At the same time, Maersk ordered a new fleet of 172 meter, 2100-TEU, twin-engine containerships that can run on methanol or traditional ultra-low sulphur fuels, and has committed to carrying 25 percent of all seaborne cargo on green-fuelled 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 [44]. 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.

First, from a "technical" perspective, according to the Export-Import Bank of Korea's Issue Report (2022) on "How to Ensure the Environmentally Compatible Competitiveness of the Domestic Shipping Industry", there is a tendency to focus on large ships and medium-sized container ships, and in particular, 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. Hence, the new ship orders of small and medium-sized shipping companies other than container ships are still insufficient. In addition to technical uncertainties, it is necessary to prepare new opportunity factors for the problem of insufficient financial resources [45]. 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 [46]. This includes long-term R&D development of new technologies and the construction of multi-test bed ships to remove

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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 [47].

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 Contract of Affreightment (COAs) promoted by energy utilities such as Korea Gas Corporation, Korea National Oil Corporation, and Korea Electric Power Corporation from 3-5 years to 5-10 years [48]. In particular, there is a need for a track record and government guarantee for coastal routes in which small shipping companies can participate. For example, governments and shippers should participate in discussions on the revision of the IMO Safety Standards for LNG Fuelled Ships (IGF Code) to support IMO listing, and efforts should be made to maintain governance based on public-private cooperation, including governments, classifications, universities and companies. In particular, track record is most important when applying unfamiliar technologies to ships, as demonstrated in the case of supporting the listing of high manganese steel, a new material for LNG fuel tanks developed by a domestic company (POSCO) in the IMO safety standards (IGF Code) and establishing an LNG bunkering system (truck-to-ship) including the installation of LNG facilities for the smooth operation of the "Green Iris" at Donghae Port (Donghae-Guangyang route, 50,000 dwt bulk carrier) [49].

Third, from an “industrial environmental” perspective, extending the duration of long-term contracts of affreightment(COAs) 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 shipowners and shippers [50]. 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 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 [51]. Therefore, the government should diversify the monopoly on LNG supply in 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 the values towards sustainability within the corporate culture 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 [52].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. What is the Niche Innovations Strategy that integrates the opportunities and challenges of the shift 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 the paradigm shift towards an eco-friendly shipping industry. Figure 6 shows the synthesis results of the niche innovations strategy. During this paradigm 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

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strengthen the opportunities to successfully make an eco-friendly shipping industry, and niche innovations will provide strategic opportunities to overcome these challenges and move in a new direction. Therefore, we will discuss innovative niche strategies that can lead to a green shipping industry through the window of opportunity during the paradigm shift through these challenges and opportunities.

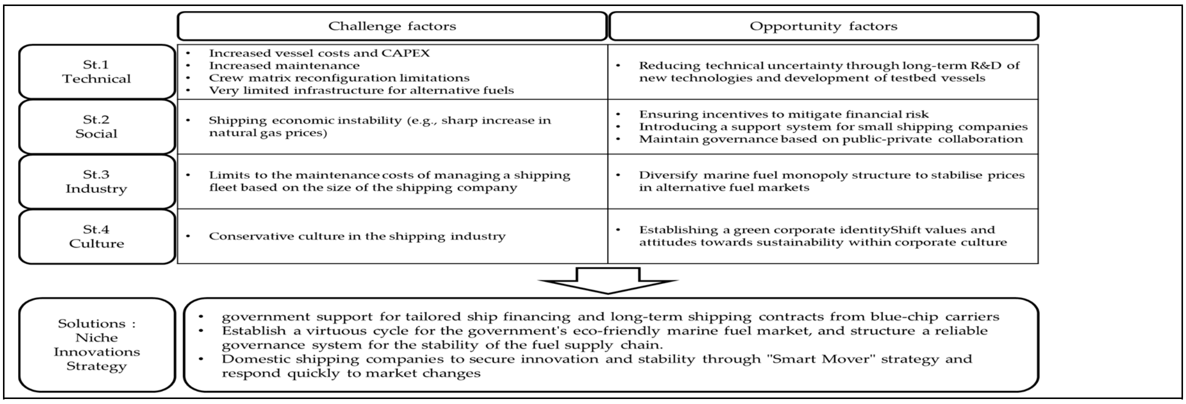

Figure 6. Finding solutions: niche innovation strategies that integrate opportunities and challenges.

4. Discussion

Shipping companies regard their ships as critical assets with a long service life, so they tend to prioritise proven empirical data and minimise risk. However, it is inevitable to take the transition because of the global climate change crisis. It is therefore necessary for shipping companies, even if they are not necessarily leaders in the shipping market, to develop a strategy to act as 'Smart Mover' that can respond to the rapidly changing market environment with a focus on 'greening [53].

From this perspective, this study proposes that ordering LNG, methanol, ammonia and hydrogen-fuelled vessels is a suitable 'window of opportunity' to interpret the socio-technical regime transition in the maritime sector as a way for domestic shipping companies to strengthen their ESG-based shipping competitiveness for the IMO 2020 sulphur oxide regulation and carbon neutrality. The challenges and opportunities accompanying the niche stream in the multi-layered interaction process were analysed separately, and the characteristics of the niche stream were summarised and suggested for improvement as follows.

First, even though shipping companies have experienced a short-term decline in freight rates due to the COVID-19, Ukraine-Russia and 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 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 to 15 years with creditworthy buyers to ensure 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 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, fuelled 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 and innovation in new environmental technologies. And then, they should ensure financial stability and respond quickly to market changes. Especially, the "first mover" strategy centred 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.

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.

5. Conclusion

This study critically analyses the transition process of the Korean shipping industry to eco-friendly marine fuels such as LNG, methanol, ammonia and hydrogen in response to the IMO 2020 sulphur oxide regulation through a socio-technical systems approach. By applying the 'window of opportunity' model of socio-technical systems 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 the 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. We summarize our findings as follows.

First, challenges in the transformation process for the shipping industry include 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 is identified that instability in the shipping economy such as the sharp rise in natural gas prices was the challenge from a social perspective. And then, there is a limit to the maintenance costs required to manage a shipping fleet based on the size of the shipping companies as an industry perspective. Lastly, in terms of corporate culture perspective, there is the conservative structure of the shipping industry.

Second, the opportunity factors of the innovation process for the shipping industry include the resolution of technical uncertainties through long-term R&D development of new technologies and the development of test-bed ships. From a social perspective, it includes 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. And then, from an industry perspective, it included diversifying the fuel monopoly structure to stabilize prices in the alternative marine fuel market. Lastly, from the corporate culture perspective, it is clarified that the main opportunities are 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 can 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, it needs to establish a virtuous cycle for the government's eco-friendly marine fuel market, and structure a reliable governance system for the stability of the fuel supply chain. Lastly, domestic shipping companies should ensure financial stability and respond quickly to market changes as a Smart Mover.

This study can be seen as an important contribution to understanding the complexity and multi-faceted 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. However, the study is only focus on the Korean context, which limits its generalizability to other regions. In addition, the reliance on literature review data does not lead to empirical findings and it might be biased.

To address these issues, future studies should be conducted in other regional contexts, reflecting the specificities of the shipping industry, to understand global patterns and further explore the long-term economic and environmental impacts of different green fuels. In particular, how to better support the green transition of the shipping industry through international cooperation and the development of policy frameworks could also be an important topic for future research.

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