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액체수소 운송선의 실운항을 위한 규제 분석 및 개정 방향

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Regulatory Analysis and Reform Directions for the Operational Deployment of Liquid Hydrogen Carriers

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Abstract >> Liquid hydrogen offers zero-carbon emissions and high energy density, making it a key fuel for maritime decarbonization. However, its cryogenic properties and flammability pose technical and safety challenges, exposing gaps in current regulations like the High-pressure Gas Safety Control Act and Harbor Act. This study proposes a unified regulatory framework addressing cryogenic storage, boil-off gas handling, and emergency protocols while aligning with international standards such as International Maritime Organization (IMO) and International Organization for Standardization (ISO). These measures aim to ensure safe hydrogen carrier deployment, infrastructure development, and broader hydrogen adoption in the maritime sector.

Key words : Liquid hydrogen(액체수소), Regulatory framework(규제 프레임워크), Cryogenic storage(초저온 저장), Hydrogen carriers(수소 운반선), Maritime decarbonization(해양 탈탄소화)

1. Introduction

As international efforts to address climate change and achieve carbon neutrality intensify, the maritime industry is increasingly required to reduce its reliance on fossil fuels and transition to sustainable alternative energy sources. The International Maritime Organization (IMO) has set a target to reduce greenhouse gas emissions from ships by 50% by 2050 compared to 2008 levels, thereby promoting the decarbonization of marine fuels and the adoption of environmentally friendly technologies[1)]. Against this backdrop, hydrogen is emerging as a key fuel in the decarbonization of the maritime sector, with hydrogen fuel cells being regarded as a promising alternative due to their zero-carbon emissions and high energy efficiency[2,3)].

In particular, liquid hydrogen is gaining attention as a suitable alternative for long-distance transport and large-scale marine fuel due to its advantages, including ease of storage and transportation, as well as high energy density[4]. However, the transportation and storage of liquid hydrogen under cryogenic conditions (-253°C) involve unique technical requirements distinct from conventional fuels. Additionally, its high flammability and explosiveness necessitate new legal and institutional approaches to ensure safety management[5]. Therefore, addressing the challenges associated with supplying liquid hydrogen to ships across land, port, and sea environments has highlighted the need for a comprehensive legal and regulatory framework to support hydrogen bunkering technologies[6].

Currently, hydrogen bunkering on land is regulated by the High-pressure Gas Safety Control Act and the Hydrogen Economy Promotion and Hydrogen Safety Management Act, which primarily focus on the safe storage and transportation of compressed or High-pressure hydrogen[7,8]. However, while these laws provide a regulatory framework for hydrogen handling, including liquid hydrogen, they primarily focus on compressed or High-pressure hydrogen and do not fully address the unique cryogenic properties of liquid hydrogen. Although liquid hydrogen falls within the scope of these regulations, key aspects such as insulation performance, boil-off gas (BOG) management, and material embrittlement risks remain insufficiently defined. This results in regulatory gaps in land-based storage, bunkering infrastructure, and emergency response measures, highlighting the need for targeted revisions to ensure the safe and efficient handling of liquid hydrogen.

Similarly, in ports, the Port Act and the Port Authority Act are applied, but they lack clear definitions for new types of energy storage and supply facilities, such as hydrogen bunkering stations, resulting in significant legal gaps[9]. Since these laws have now been categorized, it is essential to revise each regulatory framework with a stronger emphasis on safety measures, ensuring that the legal structure adequately addresses the risks associated with hydrogen storage and supply operations.

Meanwhile, the operational deployment of liquid hydrogen carriers presents several challenges that cannot be addressed within the existing legal and institutional frameworks. For instance, specialized technical standards are required for insulation technologies that account for cryogenic conditions, BOG handling and reliquefaction systems, and equipment for safe loading, unloading, and bunkering operations[5]. However, there is a lack of internationally standardized criteria for these technical requirements, underscoring the need for collaboration with regulatory authorities worldwide to establish new technical standards and safety management frameworks. However the IMO has been actively developing guidelines for the safe use of liquid hydrogen in maritime operations, including the Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk and ongoing efforts by the Sub-Committee on Carriage of Cargoes and Containers to finalize interim guidelines for hydrogen-fueled ships by 2025, significant regulatory gaps remain[10]. The lack of internationally standardized criteria for key technical requirements, particularly in bunkering operations and emergency response protocols, underscores the need for collaboration with global regulatory authorities to establish comprehensive technical standards and safety management frameworks.

This study aims to analyze the limitations of existing regulations in the context of operational deployment of liquid hydrogen carriers and propose new regulatory frameworks that reflect the unique characteristics of liquid hydrogen.

2. Regulatory framework for hydrogen transport

To enable the operational deployment of liquid hydrogen transport vessels, it is essential to comprehensively review the regulations applicable to land, port, and sea domains. These regulations form the overall framework governing the design, operation, and safety management of carriers in their respective areas, serving as a critical foundation for establishing new regulatory systems that reflect the unique characteristics of liquid hydrogen. The regulations in land, port, and sea domains each have distinct roles and purposes, making an integrated understanding of these frameworks necessary. Fig. 1 illustrates the regulatory domains along the transportation pathways between liquid hydrogen and carriers. Specifically, bunkering involves regulatory overlaps between land and port domains, while transportation within the port requires the integration of regulations from both port and sea domains.

In the land domain, representative laws include the High-pressure Gas Safety Control Act and the Hydrogen Economy Promotion and Hydrogen Safety Management Act. The High-pressure Gas Safety Control Act provides comprehensive safety standards for the manufacturing, storage, transportation, and use of high-pressure gases. It plays a crucial regulatory role in ensuring the safe management of liquid hydrogen, which is characterized by its cryogenic nature and high explosiveness. By enforcing strict regulations to prevent accidents involving High-pressure gases and safeguard public safety, this law ensures the safety of liquid hydrogen storage facilities and hydrogen bunkering systems. The Hydrogen Economy Promotion and Hydrogen Safety Management Act establishes a systematic legal framework for the advancement of the hydrogen economy and the management of hydrogen safety. This law encompasses the entire lifecycle of hydrogen, including production, storage, transportation, and utilization, while clearly defining the technical requirements related to the safety of hydrogen fuel. These regulations play a pivotal role in building the land-based infrastructure and safety management systems essential for operating liquid hydrogen carriers.

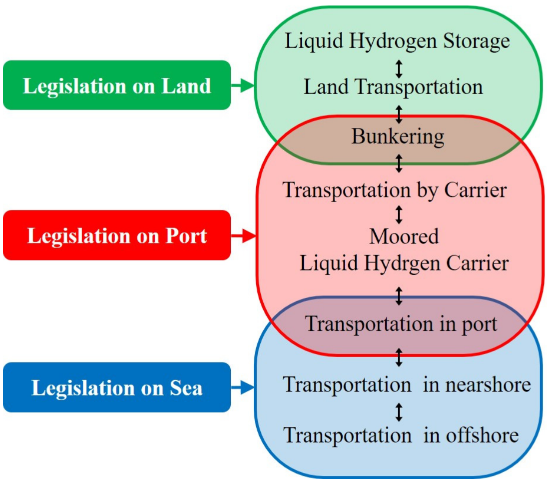

Fig. 1. Regulatory framework along liquid hydrogen transportation pathways

Key regulations applicable to ports include the Harbor Act and the Harbor Authority Act. The Harbor Act governs the designation, development, management, and usage of harbors, providing the legal basis for the installation and operation of liquid hydrogen storage and bunkering facilities within harbors. Additionally, it supports the stable distribution of new energies, such as liquid hydrogen, through the efficient management of harbor facilities and logistics operations. The Harbor Authority Act was enacted to enhance expertise in the development and operation of harbor facilities and to establish efficient management systems. This law specifically lays the groundwork for introducing infrastructure related to environmentally friendly and renewable energies in harbors, thereby promoting the installation of new energy storage and supply facilities, such as those for liquid hydrogen.

Key regulations governing the sea domain include the Ship Act, the Ship Safety Act, and the Maritime Safety Act. The Ship Act defines the requirements for ship registration, nationality, and management standards, establishing the legal framework for ensuring that new types of vessels, such as test vessels, are suitable for operation. The Ship Safety Act provides clear standards for maintaining seaworthiness and ensuring the safe operation of ships. It includes specific requirements for the design and operation of vessels transporting hazardous materials, such as liquid hydrogen. This law outlines technical requirements, such as the management of BOG and ensuring stable transportation under cryogenic conditions. The Maritime Safety Act offers a comprehensive management framework for the safe operation of vessels, aiming to prevent maritime accidents and manage potential risks. It defines the legal foundations and safety management requirements necessary for the safe operation of liquid hydrogen carriers in maritime environments.

Fig. 2 summarizes the regulations applicable to each domain.

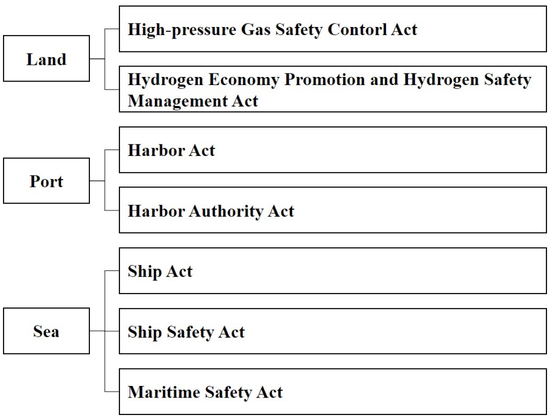

Fig. 2. Regulations applicable to land, port, and sea domains

3. Analysis of legal gaps and challenges

3.1 Technical and safety challenges

The transportation and storage of liquid hydrogen present unique challenges that necessitate specialized technical solutions. Maintaining hydrogen in its liquid state at -253°C requires advanced cryogenic technologies to ensure safe and efficient handling[4]. A critical technical challenge is cryogenic insulation, essential for minimizing heat ingress and BOG generation. Unlike conventional fuels, liquid hydrogen storage depends on multi-layer vacuum insulation systems; however, current regulations lack standardized criteria for insulation efficiency, allowable heat leakage, and permissible BOG release rates[11]. This regulatory gap leads to inconsistent performance standards and operational uncertainties in hydrogen storage and transportation. Material selection for storage tanks, pipelines, and transfer systems is also crucial due to the severe embrittlement risks at cryogenic temperatures[12]. While some international guidelines offer general recommendations, a unified regulatory framework specifying material fatigue resistance, mechanical property requirements, and long-term durability criteria is absent. This absence poses challenges in ensuring the structural integrity and operational safety of liquid hydrogen infrastructure under extreme conditions.

The High-pressure Gas Safety Control Act and the Hydrogen Economy Promotion and Hydrogen Safety Management Act provide safety standards primarily for compressed or High-pressure gases. However, they do not adequately address the unique physical and chemical properties of liquid hydrogen, such as its cryogenic and high-risk characteristics. Liquid hydrogen's high flammability and explosiveness necessitate specialized safety measures. Yet, rapid leak detection, emergency venting mechanisms, and hydrogen-specific fire suppression systems remain underdeveloped. Compared to other chemical fuels, liquid hydrogen exhibits distinct physical and chemical properties that require specialized handling and safety measures[11]. Unlike liquefied natural gas (LNG) or conventional fossil fuels, liquid hydrogen has a much lower boiling point, requiring advanced cryogenic storage technologies to prevent excessive BOG generation. Additionally, its extremely low density (0.07 g/cm^3 in liquid form) necessitates larger storage volumes, making transportation and bunkering infrastructure more challenging than for fuels like LNG or synthetic hydrocarbons[11]. From a chemical reactivity perspective, hydrogen has the widest flammability range (4-75% in air), significantly higher than that of methane (5-15%) or gasoline vapors (1.4-7.6%), making it more prone to accidental ignition. Furthermore, hydrogen's minimum ignition energy (0.017 mJ) is much lower than that of conventional fuels, increasing the risk of ignition from minor electrostatic discharges. Unlike hydrocarbon-based fuels that produce visible flames when burned, hydrogen flames are nearly invisible, complicating fire detection and suppression efforts.

3.2 Legal gaps in land, port, and sea regulations

A review of the regulations applicable to land, port, and sea domains for the operational deployment of liquid hydrogen carriers reveals unique legal gaps and limitations in each domain. These gaps hinder consistency in the design, operation, and safety management of carriers and act as significant barriers to the commercialization of liquid hydrogen as a new energy transport medium.

In the land domain, the High-pressure Gas Safety Control Act and the Hydrogen Economy Promotion and Hydrogen Safety Management Act serve as the primary legal foundations. However, neither law adequately reflects the unique characteristics of liquid hydrogen. The High-pressure Gas Safety Control Act primarily provides safety standards for the manufacturing, storage, and transportation of High-pressure gases, but it does not explicitly address the technical requirements for storage and transportation under cryogenic conditions. This results in a lack of legal support for ensuring the safety of land-based infrastructure, such as storage facilities and hydrogen bunkering systems, required for handling liquid hydrogen. Similarly, the Hydrogen Economy Promotion and Hydrogen Safety Management Act regulates the hydrogen industry broadly but lacks detailed safety standards or operational guidelines tailored to the specific challenges of cryogenic liquid hydrogen.

In the port domain, the Harbor Act and the Harbor Authority Act are the primary regulations. The Harbor Act provides general provisions related to the designation, development, and management of harbors, while the Harbor Authority Act establishes a legal framework for efficient harbor facility operations and management. However, neither law offers specific standards for new infrastructure based on advanced technologies, such as hydrogen bunkering facilities. There is a notable absence of clear legal guidelines regarding the equipment and procedures required for the storage and bunkering of liquid hydrogen in ports, which poses significant challenges to ensuring its safe handling and transportation within port environments.

In the sea domain, legal gaps are also evident. The Ship Act, Ship Safety Act, and Maritime Safety Act govern ship registration, management, and operations, but they primarily focus on general vessel requirements and fail to provide specific provisions for the transportation of high-risk materials such as liquid hydrogen. While the Ship Safety Act offers general safety standards for the transportation of hazardous materials, it does not include detailed regulations addressing the cryogenic properties of liquid hydrogen or technical requirements, such as boil-off gas management. Similarly, the Maritime Safety Act aims to ensure safe ship operations and prevent maritime accidents, but it lacks specialized guidelines for the design and operation of ships handling liquid hydrogen.

4. Proposed regulatory enhancements for hydrogen transport challenges

4.1 Regulatory enhancements and technical framework for hydrogen transport

Table 1 summarizes the legal gaps, technical requirements, and proposed solutions across various regulations relevant to liquid hydrogen transportation and storage. The High-pressure Gas Safety Control Act lacks cryogenic storage and BOG management standards, requiring the addition of specific technical criteria. The Hydrogen Economy Promotion and Hydrogen Safety Management Act fails to address the unique properties of liquid hydrogen, necessitating operational guidelines for bunkering and emergency protocols. The Harbor Act and Harbor Authority Act lack standards for liquid hydrogen storage and bunkering facilities in ports, highlighting the need for installation, operation, and logistics integration guidelines. The Ship Act and Ship Safety Act require new standards for designing, certifying, and operating liquid hydrogen carriers, particularly regarding cryogenic operations and safety systems. Lastly, the Maritime Safety Act does not provide emergency response or environmental protection measures for liquid hydrogen, necessitating the development of response manuals and environmental management frameworks. Collectively, these gaps underscore the need for a comprehensive regulatory framework tailored to the unique challenges of liquid hydrogen.

4.2 Interlinking regulatory frameworks across land, port, and sea

Table 2 highlights the gaps, key elements, and proposed solutions in regulatory interactions across the land, port, and sea domains for liquid hydrogen transportation. In the land-port interaction, the key focus is on aligning transport equipment and operational standards, but gaps include the lack of standardization between transport infrastructure and bunkering facilities and undefined responsibilities for transfer-related accidents. Proposed solutions involve developing integrated transport guidelines and clarifying safety management responsibilities. In the port-sea interaction, the integration of bunkering technology with vessel safety standards is essential, yet inconsistencies in safety requirements and a lack of joint accident response protocols pose challenges. Solutions include creating standardized technical guidelines and establishing emergency response systems between port and sea. For land-sea interactions, aligning safety and technical standards is critical, but discrepancies in cryogenic and BOG management standards and unclear responsibilities for boundary incidents remain problematic. Addressing these issues requires the development of integrated cryogenic transport guidelines and clearly defining responsibilities for incidents at the land-sea interface. Collectively, these measures aim to ensure seamless regulatory coordination across all domains.

The overall integration of regulatory frameworks for liquid hydrogen transportation requires establishing a unified system that links the land, port, and sea domains while ensuring alignment with international standards such as those set by the IMO and the International Organization for Standardization (ISO). Currently, the absence of a cohesive regulatory framework results in fragmented regulations across these domains, leading to inconsistencies that hinder efficient oper-

Table 1. Analysis of legal gaps and solutions in hydrogen transport regulations

Legislation	Gaps	Technical requirement	Problem definition	Proposed solution
High-pressure Gas Safety Control Act	Lack of standards for cryogenic storage and transportation	Cryogenic insulation technology Boil-off gas (BOG) management systems	Lack of safety management standards considering cryogenic characteristics of liquid hydrogen Legal basis insufficient for facility design and operation	Add standards for cryogenic insulation and BOG management Develop detailed safety regulations for liquid hydrogen storage facilities and transport equipment
Hydrogen Economy Promotion and Hydrogen Safety Management Act	Insufficient consideration of physical and chemical characteristics of liquid hydrogen	Operational guidelines for liquid hydrogen bunkering facilities Safety management and emergency response protocols	Operational guidelines reflecting the specific characteristics of cryogenic liquid hydrogen are absent Legal uncertainty for hydrogen bunkering facilities	Introduce standards for the design and operation of liquid hydrogen bunkering facilities Establish emergency response protocols
Harbor Act	Absence of standards for liquid hydrogen storage and bunkering facilities in ports	Installation requirements for liquid hydrogen storage facilities in ports Safety inspection and maintenance guidelines	Lack of clear regulations to ensure the safety of port infrastructure Delay in adoption of renewable energy-based facilities	Add standards for renewable energy storage facilities in ports Develop operational guidelines for liquid hydrogen bunkering and storage facilities
Harbor Authority Act	Lack of regulations for new energy storage and supply infrastructure	Efficient management systems for bunkering infrastructure Integration with port logistics	No legal basis for efficient management and integration of new energy facilities such as liquid hydrogen	Develop support systems for introducing renewable energy infrastructure in ports Create integrated management guidelines for port logistics
Ship Act	Lack of standards for design and operation of liquid hydrogen carriers	Standards for cryogenic vessel design Safety valves and monitoring systems	Insufficient regulations reflecting the characteristics of liquid hydrogen in vessel design Ambiguities in technical requirements during ship registration and certification	Introduce standards for the design and certification of liquid hydrogen carriers Establish ship registration procedures considering technical specifics
Ship Safety Act	Absence of safety standards and technical requirements for liquid hydrogen carriers	BOG management systems Safe operation procedures under cryogenic conditions	Lack of detailed safety standards reflecting the cryogenic and flammable characteristics of liquid hydrogen Insufficient legal framework to prevent accidents during operation	Develop safety standards for liquid hydrogen carriers Introduce safety technologies and procedures for cryogenic and BOG management
Maritime Safety Act	Lack of emergency response procedures and environmental protection guidelines for liquid hydrogen	Emergency response procedures Safety management system for environmental protection	No response guidelines for accidents involving liquid hydrogen Lack of environmental impact assessment and recovery procedures	Establish emergency response manuals for liquid hydrogen spills Develop guidelines for environmental protection and accident recovery

Table 2. Regulatory interactions and solutions for hydrogen transport across domains

Interaction domain	Key elements	Gaps identified	Proposed solutions
Land-port interaction	Liquid hydrogen transport from land storage to port bunkering facilities Equipment and operational standards alignment	Lack of standardization between transport infrastructure and bunkering facilities Undefined responsibilities for accidents during transfer	Develop integrated transport guidelines between land and port Clarify responsibilities and boundaries for safety management
Port-sea interaction	Supplying liquid hydrogen from port bunkering facilities to maritime vessels Integration of bunkering technology and safety standards	Inconsistencies in safety standards for bunkering facilities and vessels Lack of joint response protocols for accidents	Create standardized technical guidelines for bunkering operations Establish joint emergency response systems for port and sea
Land-sea interaction	Direct supply of liquid hydrogen from land-based production to maritime vessels Alignment of safety and technical standards	Discrepancies in technical standards for cryogenic and BOG management Undefined responsibilities for incidents at land-sea boundaries	Develop integrated cryogenic transport guidelines Define responsibilities for incidents at the land-sea interface

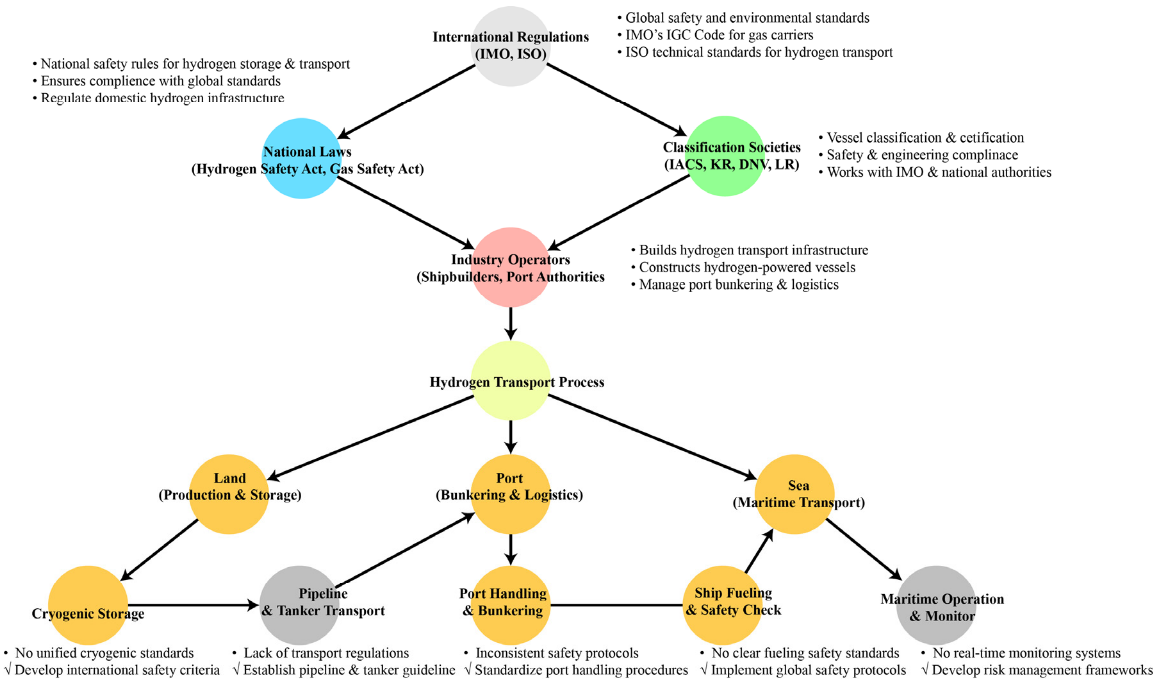

Fig. 3. Towards a unified regulatory framework for liquid hydrogen transport

ations and the commercialization of liquid hydrogen as a sustainable energy source. Additionally, misalignment with international standards creates barriers to global market access and delays the adoption of advanced technologies. To address these gaps, a comprehensive regulatory framework should be designed to harmonize the requirements of land, port, and sea regulations, ensuring seamless integration and interoperability. National standards must also be updated to align with international norms, fostering global consistency and promoting the safe, efficient, and commercially viable transport of liquid hydrogen. Fig. 3 illustrates this approach by presenting a unified regulatory framework that interconnects these domains, ensuring regulatory coherence and alignment with international standards. Such an integrated approach will not only address current regulatory inefficiencies but also support the broader adoption of hydrogen as a critical component of the energy transition.

5. Conclusion

As the maritime industry moves toward decarbonization, liquid hydrogen stands out as a zero-emission, high-energy fuel. However, its cryogenic nature and safety challenges necessitate advanced technical solutions and regulatory updates. This study highlights key regulatory gaps across land, port, and sea domains and proposes targeted enhancements to address these issues.

Current regulations, including the High-pressure Gas Safety Control Act, Hydrogen Economy Promotion and Hydrogen Safety Management Act, Harbor Act, and maritime laws, lack provisions for liquid hydrogen's cryogenic and high-risk characteristics. Significant updates are needed to address technical and safety standards for bunkering, storage, and carrier operations. To overcome these limitations, this study proposes a unified regulatory framework that integrates the requirements of land, port, and sea domains. Key recommendations include the development of cryogenic insulation standards, BOG management systems, emergency response protocols, and environmental protection guidelines. Furthermore, aligning national standards with international frameworks, such as those established by the IMO and ISO, is critical for ensuring global consistency and fostering the commercialization of liquid hydrogen as a viable marine fuel.

The proposed regulatory framework addresses key gaps to enable safe liquid hydrogen carrier deployment, support infrastructure development, and advance hydrogen adoption, helping the maritime industry achieve decarbonization and sustainability goals.

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