International Journal of Hydrogen Energy 291 (2026) 158510

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

System-Level Knowledge Gaps in Liquid Hydrogen Storage Integration for Maritime Applications

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ARTICLE INFO

Handling Editor: Dr. E.A. Veziroglu

Keywords:
Liquid Hydrogen (LH_2)
Storage System Integration
Knowledge Gaps
Maritime Decarbonization
Research Roadmap

ABSTRACT

Liquid hydrogen (LH_2) is considered an environmentally sustainable fuel for maritime decarbonization because it does not directly emit greenhouse gases (GHGs). However, integrating LH_2 onboard ships poses yet unresolved technical, operational, and regulatory challenges. Considering this, the status of research on LH_2 tank integration in maritime applications is systematically reviewed in this study, with an emphasis on identifying and structuring existing knowledge gaps. It is observed that, despite significant advancements in individual domains, there is a considerable underrepresentation of system-level research on integrating LH_2 storage systems onboard ships and the associated operating conditions. Furthermore, the analysis conducted in this study reveals a substantial gap between current research and the requirements for large-scale implementation. Hence, this paper proposes a research roadmap based on these findings. It outlines key focus areas for further research, including, but not limited to, integrated system modeling, pilot-scale demonstration, and development of standardized design and safety protocols.

1. Introduction

The maritime sector is undergoing a major transition driven by global decarbonization targets and increasingly stringent emissions legislation. International shipping, which contributes about 3% of global greenhouse gas emissions, is expected to shift to fuels that emit less or no greenhouse gases [1]. Of the many energy sources that can be used as alternatives, hydrogen seems promising because of its zero-emission nature and high gravimetric energy density [2]. Different on-board hydrogen storage options such as compressed, liquefied, cryo-compressed, and metal hydrides, exist. Liquefied hydrogen (LH_2) is often the focus of discussion because of its high volumetric energy density. Furthermore, space constraints on ships necessitate an option that offers high volumetric energy density. Unlike conventional marine fuels, LH_2 must be stored and maintained at cryogenic temperatures (approximately 20 K). Consequently, LH_2 must be stored in specialized fuel tank technologies. This introduces a number of engineering challenges, including thermal concerns, material selection, and safety issues, among others. In particular, the storage and handling of LH_2 onboard ships is a complicated issue that is more than just substituting a fuel tank; rather, it involves a complex system-level redesign problem involving structural, thermal, and operational considerations. This has led to increasing research interest in LH_2 storage technologies and their application in maritime environments.

Existing studies have investigated different aspects of LH_2 systems, such as cryogenic tank design, insulation technologies, boil-off gas management, and safety risk assessment [3–6]. However, a large part of the current research remains fragmented, with individual studies considering isolated subsystems rather than the integrated behavior of LH_2 storage within complete ship systems. As a result, the interaction between tank design, ship design, operational constraints, and regulatory frameworks is not fully understood yet.

One particularly pressing challenge is integrating LH_2 storage systems into ship hull structures. Due to the relatively low volumetric energy density of LH2, its storage occupies much more space than conventional fuel. This affects both the ship's design and performance. This constraint leads to complex trade-offs between energy storage efficiency, structural feasibility, and operational performance, which are not yet fully addressed in the literature [7,8]. In addition, the dynamics of the marine environment, often ignored, present further challenges. Ship motions such as roll, pitch, and heave affect the behavior of fuels inside the tank, causing sloshing and varying boil-off rates [9]. These effects, which are tightly coupled with system-level performance, are rarely integrated into unified design or analysis frameworks.

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https://doi.org/10.1016/j.ijhydene.2026.158510
Received 3 June 2026; Received in revised form 4 September 2026; Accepted 2 November 2026
Available online 9 November 2026
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Open access funding enabled and organized by Projekt DEAL.

From a regulatory point of view, system development and implementation are further complicated by the lack of fully established standards for LH_2-fueled ships. There are general guidelines for alternative fuels under the International Maritime Organization framework, but specific rules for LH_2 storage integration, safety distances, and operational procedures are still being developed [10,11]. This regulatory uncertainty adds another layer of complexity in the design and deployment of LH_2-based marine systems.

Despite rapid advances in individual technological components, there is a clear gap in the literature regarding a holistic, system-level understanding of LH_2 storage integration in maritime applications. More specifically, there is limited synthesis of how thermal behavior, structural design, safety requirements, operational constraints, and regulatory frameworks interact within a unified ship system. Consequently, this study provides a systematic review of LH_2 storage integration in ships with particular emphasis on system interactions and cross-cutting engineering issues. A bibliometric analysis is employed to map the research landscape and identify dominant thematic clusters, followed by a critical synthesis of key knowledge gaps in the thermal, structural, operational, and regulatory areas. The main contribution of this review is therefore twofold: first, it consolidates the existing knowledge on LH_2 tank technologies and their application in maritime environments; second, it identifies and structures the key integration gaps that currently limit the development of fully optimized LH_2-fueled ship systems. Therefore, the novelty of this work lies in offering new perspectives on knowledge gaps in the integration of LH_2 storage systems onboard ships through a conceptual framework. Furthermore, this work reveals overlooked problems and unexplored areas. This establishes a basis for future research directions in the development and implementation of integrated cryogenic fuel systems for sustainable shipping.

2. Data and Methods

This research employs a structured, systematic literature review to identify and analyse knowledge gaps in the onboard integration of liquid hydrogen (LH_2) storage systems for ships. The methodology is formulated to guarantee transparency, reproducibility, and comprehensive coverage across relevant engineering and regulatory domains.

2.1. Literature Search Strategy

A multi-database search strategy was used to retrieve peer-reviewed articles and conference papers. The main databases used were Scopus and Web of Science. Additional searches were also conducted on Google Scholar to identify further studies and grey literature that may be relevant but not found in the main databases. A combination of keywords related to the subject matter was used to scan the first 100 results sorted by relevance in Google Scholar. To remain relevant, the search was limited to publications in English and focused on the period from 2010 to 15 May 2026, which covers more than 15 years of research advancements - and reflects growing interest - in hydrogen as a maritime fuel in the context of global decarbonization efforts. The search terms used were a combination of concepts related to LH_2 storage and maritime applications, combined with Boolean operators to maximize retrieval. The full Web of Science search string is provided in Appendix A, and similar strategies were applied to the other databases. All identified records were imported to Zotero for deduplication before screening.

2.2. Screening and Selection Criteria

The initial search returned 946 articles after filtering by document type, language, and research area. The retrieved literature was screened according to a PRISMA-based methodology adapted for bibliometric reviews. The selection pathway is shown in Fig. 1 following the PRISMA

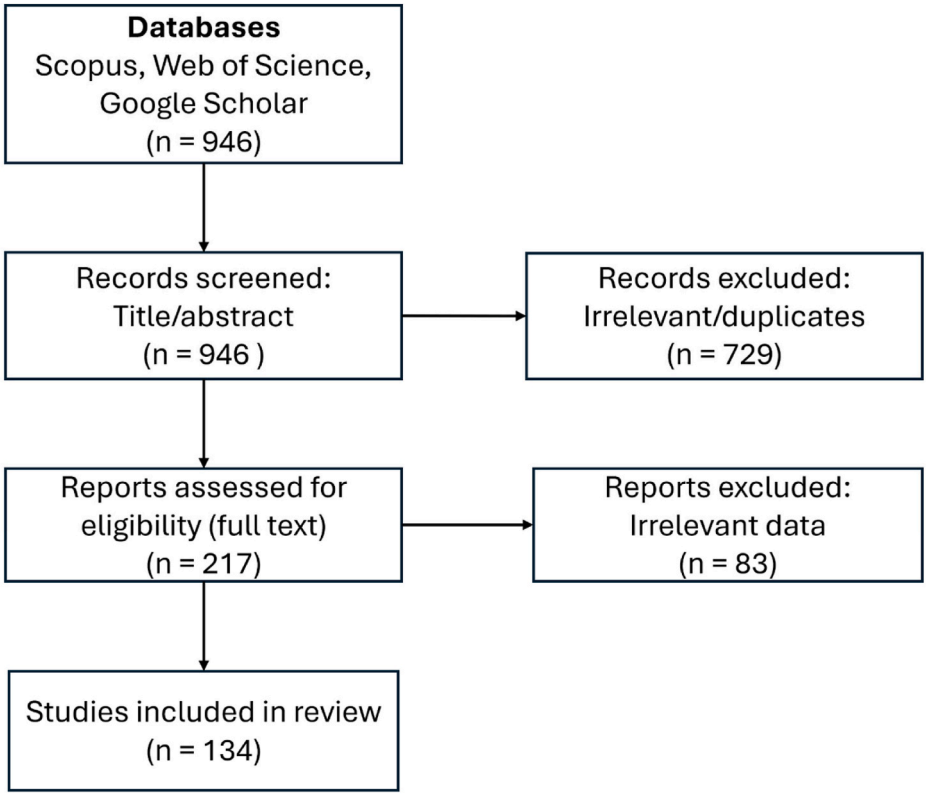


Fig. 1. Flow diagram of the literature review process.

2020 format. Firstly, titles, keywords, and abstracts were screened to exclude studies not related to maritime applications or LH_2 systems specifically. In the second stage, the full-text screening was performed to check relevance to onboard LH_2 storage system integration. Eligible studies addressed at least one of the following areas: (i) design/performance of LH_2 storage tank, (ii) thermal management/behavior of boil-off gas, (iii) structural/safety integration in marine environments, (iv) operational, lifecycle, or regulatory aspects of hydrogen-fueled ships. Articles were excluded if they were duplicates, non-English, or focused solely on land-based hydrogen systems without transferable maritime relevance unless they provided foundational principles applicable to shipboard integration. Following this extensive selection process, the final dataset was composed of 134 documents.

2.3. Data Extraction and Classification

For each selected publication, relevant information was systematically extracted and organized into predefined thematic domains: (i) tank technology and design, (ii) thermal and cryogenic behavior, (iii) structural integration implications, (iv) safety and risk assessment, (v) operational and lifecycle considerations, and (vi) regulatory and classification frameworks. Moreover, each study was evaluated based on its methodological approach (experimental, numerical, or analytical), scale of analysis (component-level, subsystem-level, or system-level), and degree of validation. A structured gap-identification framework was applied to evaluate limitations across the literature systematically. The gaps identified were grouped into five categories:

- Technical gaps – limitations in physical modeling, experimental validation, or engineering assumptions
- Integration gaps – lack of coupling between subsystems (e.g., tank–ship interaction, thermal–structural coupling)
- Operational gaps – limited understanding of real-world ship operations, maintenance, and fuel consumption dynamics
- Regulatory gaps – absence of specific or harmonized standards, notably within the International Maritime Organization framework
- Data and validation gaps – lack of experimental, pilot, or full-scale operational datasets.

This framework was applied to each publication to identify explicit and implicit gaps. These gaps were then synthesized across studies to find recurring patterns and systemic limitations.

2.4. Synthesis and Cross-Domain Bibliometric Analysis

A cross-domain synthesis was performed to identify overarching trends and interdependencies across thematic areas in the final dataset. This was done using data from the dataset to perform a co-occurrence analysis of keywords. A network visualization map (Fig. 2) was created using VOSviewer, with a minimum keyword occurrence threshold of 3. By mapping relationships between different thematic clusters, system-level inconsistencies were identified. Emphasis was placed on identifying disconnects between component-level research and system-level ship integration. This step enabled the development of a consolidated understanding of how individual technological advancements align—or fail to align—with real-world maritime application requirements.

2.5. Limitations of the Methodology

Despite the systematic and structured nature of this review, there are a number of limitations to note. First, the dependence on published literature may introduce bias towards topics well documented in the literature, perhaps neglecting emerging or proprietary industrial

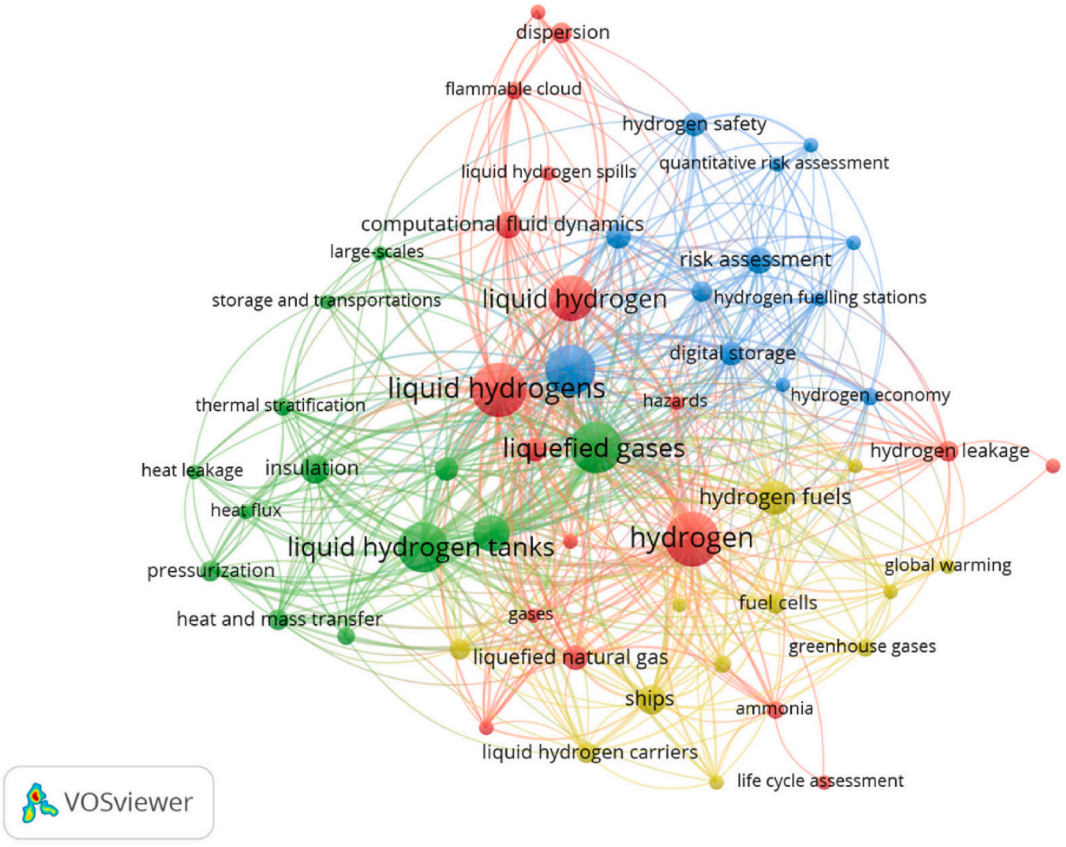


Fig. 2. Co-occurrence of keywords mapping (https://vosviewer.com/).

developments. Second, hydrogen technologies are evolving rapidly, and some of the recent advancements may not yet be reflected in the academic literature. Finally, the classification of gaps involves some interpretative judgment, although this was mitigated by the use of predefined criteria for categorization. In general, the methodology provides a systematic framework for reviewing LH_2 integration in maritime applications and identifying key knowledge gaps. The study enables a detailed technical analysis as well as a high-level system synthesis by combining thematic classification with a formal gap identification approach, supporting the development of a comprehensive research roadmap for future work in LH_2-fueled shipping systems.

3. System-Level Knowledge Gaps

In the following subsections, the cross-domain system-level knowledge gaps are described. This is done using the already highlighted thematic domains.

3.1. Tank Technologies and Design Approaches for LH_2 Storage

The development of liquid hydrogen (LH_2) storage systems for maritime transport has evolved by adapting cryogenic containment principles originally established in aerospace and industrial hydrogen systems. Studies of LH_2 storage behavior indicate that vacuum insulation and controlled boil-off management, mature in non-maritime applications, are fundamentally applicable in transport systems. However, their performance is increasingly sensitive to dynamic environmental conditions when deployed in mobile platforms such as ships [9,12–14]. This shift from static or aerospace environments to marine operation introduces a key change in design emphasis, moving from purely thermal efficiency to coupled thermal-structural resilience under motion-induced loading.

In this evolving design space, vacuum-insulated Type-C pressure vessels have become a prevailing baseline solution for shipboard LH_2 storage. Across ship integration and demonstrator-oriented studies, there is a strong consensus that Type-C systems provide a practical balance between safety, regulatory maturity, and cryogenic containment reliability under maritime operating conditions [11,15–18]. Several studies show that such tanks retain their structural integrity under combined thermal contraction and hydrodynamic excitation, including sloshing and vessel motion effects [13,19,20]. However, other studies consistently point to a fundamental trade-off: while Type-C tanks exhibit good performance in pressure resistance and safety margins, their cylindrical shape and corresponding structural reinforcement result in poor use of ship hull volume, making them ill-suited for space-constrained vessel designs [7,15,21].

This spatial constraint has prompted exploration of alternative containment approaches, particularly conformal LH_2 tank concepts [22,23]. Conceptual studies of non-cylindrical tank geometries show that adaptation of tank shape to hull curvature can significantly improve volumetric efficiency and flexibility of integration into ship structures [7]. These approaches move the design philosophy from independent pressure containment to hull-integrated fuel storage. However, the evidence of the potential benefits so far is mainly computational, without mature experimental validation under realistic maritime operating conditions. This leads to a well-defined gap between the conceptual geometric optimization and actual deployment, showing that conformal systems are still at a pre-implementation stage.

A more fundamental limitation is the way in which performance is evaluated across both traditional and alternative tank concepts. Existing studies mostly treat tank design as a stand-alone engineering problem, concentrating on metrics such as boil-off rate, thermal insulation performance, or structural stress resistance, without integrating these results within full ship-system contexts [16,24]. When operational parameters such as fuel consumption dynamics, pressure fluctuations, and ship environmental conditions are introduced, strong interdependencies among safety margins, insulation performance, and structural integrity emerge. However, such interdependencies are seldom represented in a unified optimization framework, resulting in design methodologies that do not systematically address trade-offs among efficiency, safety, and structural integrity in realistic mission scenarios.

Furthermore, the transfer from analytical and numerical studies to realistic maritime applications is limited due to the lack of experimental validation at ship-relevant scales. Most of the available experimental data on LH_2 tank technologies are performed in controlled or quasi-static conditions at laboratory-scale or adapted from non-maritime applications [24,25]. Hence, there are still major uncertainties on scalability, long-term operational stability, and boil-off behavior under real voyage conditions. This experimental gap constitutes a broader structural challenge for the field in that the transition from laboratory-validated cryogenic systems to fully integrated maritime LH_2 fuel infrastructures has only been partially demonstrated. A summary of the key tank technology and design approach knowledge gaps is presented in Table 1.

3.2. Structural Integration of Liquid Hydrogen Storage Systems in Ship Design

The structural integration of liquid hydrogen (LH_2) storage systems is a major challenge in the development of hydrogen-powered ships. This is due to the combined effects of cryogenic operating conditions, volumetric inefficiency, and stringent safety requirements. Consequently, research has focused on space and weight optimization, thermal performance, and the structural integrity of cryogenic storage technologies [7,8,16,26]. Despite these advances, the literature remains heavily fragmented across disciplinary boundaries. Most studies treat LH_2 storage systems as isolated engineering components rather than fully integrated elements of ship structures [8,15,18]. Consequently, current research offers limited insights into how cryogenic tanks interact with the surrounding hull structure under operational conditions. This decoupled approach significantly limits the ability to assess the actual impact of LH_2 storage on overall vessel design. In practical marine applications, LH_2 tanks must be integrated into the hull or deck of the ship, leading to complex interactions among thermal contraction, local stress concentrations, structural stiffness mismatches, and global hull response. However, the interplay among these coupled effects has not been adequately addressed in the existing research [8,27].

A common shortcoming in the literature is the lack of validated structural coupling models capable of combining cryogenic tank behavior with conventional naval architectural analysis [18]. While standard ship design procedures provide reliable techniques for assessing global hull strength, fatigue, and hydrodynamic loading, these procedures are not directly applicable to cryogenic applications where thermal and mechanical loading conditions are significantly different. In particular, differential material contraction at cryogenic temperatures, thermally induced stresses, and dynamic load transfer between the tank and supporting hull structures are not well described by standard

Table 1
Tank technologies and design approach knowledge gaps.

Aspect	Current state of knowledge	Identified gap
Type-C tanks	Mature cryogenic technology	Poor ship space optimization
Conformal tanks	Conceptual studies	Lack of experimental validation
Insulation systems	Well-developed materials	No long-term maritime performance data
Design methodology	Component-based design	No integrated ship environmental conditions
Structural integration	Partial studies	No coupled hull-tank modeling

structural assessment procedures [16,18].

In parallel, several studies have highlighted the significant influence of LH_2 storage on ship stability, payload capacity, and spatial arrangement [7,15,28,29]. Considering that the volumetric energy density of hydrogen is substantially lower than that of traditional marine fuels, LH_2 storage requires significantly larger tank volumes, thus affecting hull form, cargo/tank placement, and the overall ship layout. Nevertheless, much of the literature on conceptual design is based on simplified assumptions for the location of tanks and not detailed in terms of the optimization of the trade-offs among the capacity of fuel storage, utilization of cargo space, structural efficiency, and stability performance [7,8,21,30]. This has left many proposed ship concepts insufficiently validated from an integrated ship design perspective.

Another major gap pertains to the limited availability of experimental and operational validation. Present knowledge is largely derived from numerical simulations, laboratory-scale experiments, and conceptual design studies [27,31]. This leads to considerable uncertainty in long-term structural behavior under realistic marine operating conditions, especially with respect to cyclic thermal loading, sloshing effects, vibration, and wave-induced hull motions. Thus, the absence of full-scale validation reduces confidence in the durability and reliability of proposed structural integration approaches.

The literature also points out a persistent gap in the structural and safety-oriented design methodologies. Cryogenic spill scenarios, fire protection requirements, collision resistance, and blast mitigation impose additional constraints on tank placement and structural arrangement. However, safety analyses are often conducted independently of the structural design/layout of ships, leading to isolated design processes that neglect potentially critical interdisciplinary interactions [27,32–35]. This separation hinders the development of integrated solutions that can simultaneously satisfy structural and safety requirements.

From a broader systems perspective, the lack of common design approaches presents a major barrier to advancing LH_2-powered shipping. Although considerable progress has been made in individual areas of cryogenic tank technology, insulation systems, and conceptual vessel design [3,6,17,36,37], there is still a clear lack of holistic frameworks combining cryogenic behavior, structural mechanics, hydrodynamic performance, and ship-level optimization in a single analytical environment. Overcoming this limitation will likely require developing multi-physics and multi-disciplinary design approaches that can couple thermal, mechanical, and hydrodynamic phenomena across multiple operational scales [27]. Table 2 presents a summary of the structural integration knowledge gaps.

3.3. Thermal Management and Boil-Off Gas Handling

Thermal management remains a central challenge in liquid hydrogen (LH_2) storage for maritime applications because of the stringent cryogenic conditions required to keep hydrogen in the liquid state. A major limiting phenomenon is the generation of boil-off gas (BOG) from unavoidable heat ingress through tank walls and insulation systems. BOG formation has been extensively studied using analytical and numerical approaches, focusing on heat transfer mechanisms, insulation performance, and tank geometry optimization [37–44]. Together, these works show that BOG behavior is strongly governed by coupled thermodynamic and thermal transport processes within the storage system.

Although current models can accurately describe thermodynamic behavior, they are mostly derived under the assumption of static or quasi-steady storage conditions. This is a significant limitation for maritime applications where ship motions - such as rolling, pitching, and heaving - and variable ambient temperature introduce time-dependent boundary conditions. Such dynamics can change internal fluid dynamics, enhance mixing, and possibly alter local heat transfer rates, thereby affecting evaporation and pressure evolution. Nevertheless, the coupling of vessel motion and LH_2 thermal response is still not sufficiently studied in the literature [14,45,46], with only a few studies addressing coupled sloshing-evaporation mechanisms in ship-relevant configurations [9,20,47–52]. Consequently, present modeling frameworks may not fully capture operational variability under real sea states.

Furthermore, approaches to managing BOG have been proposed, including reliquefaction, controlled venting, and use in propulsion systems such as engines or fuel cells [53–58]. While each approach has been extensively researched, it has been done in isolation rather than as part of an integrated ship energy system. Hence, the coupling of time-varying BOG production with dynamic propulsion or intermittent fuel demand is rarely considered. This leads to simplified system representations that do not account for feedback effects between storage conditions and energy conversion subsystems, thereby limiting the applicability of existing models for operational decision-making and system optimization.

A further limitation is the lack of experimental validation at scales representative of shipboard LH_2 systems. Most studies are based on computational simulations or laboratory-scale experiments, which do not fully reproduce the thermal inertia, boundary conditions, or operational variability of large cryogenic tanks onboard ships [54,57,59–61]. This leads to uncertainties in extrapolating results to full-scale applications, particularly under cyclic loading and long-term marine exposure. The limited availability of large-scale experimental datasets further constrains validation of numerical models, reducing confidence in predicted long-term performance and reliability of proposed thermal management strategies.

In general, the understanding of the thermal behavior of LH_2 at the component level has advanced significantly; however, a clear imbalance exists between the detailed understanding at the component level and the lack of system-level integration studies. Specifically, the lack of dynamic modeling frameworks that capture vessel motion, operational variability, and energy system coupling is a significant barrier to the real-world deployment of LH_2 technologies in maritime environments. Addressing these gaps will require interdisciplinary approaches combining insights from cryogenic and marine engineering, as well as the generation of validated experimental datasets under realistic operating conditions. A summary of the key identified knowledge gaps in liquid hydrogen thermal management and BOG handling is provided in Table 3.

Table 2
Structural integration knowledge gaps.

Aspect	Current state of knowledge	Identified gap
Tank design	Well-developed cryogenic tank concepts	Limited ship-level integration studies
Structural coupling	Basic load analysis available	No validated hull-tank integration models
Space utilization	Conceptual arrangements exist	No optimization of cargo-fuel trade-offs
Stability analysis	Conventional methods applied	LH_2-specific stability effects are underexplored
Fatigue	Limited simulation studies exist	No long-term operational validation
Safety integration	Separate safety models exist	No unified structural-safety framework

Table 3
Identified knowledge gaps in thermal management and BOG handling.

Aspect	Current state of knowledge	Identified gap
BOG generation	Well-modelled under static conditions	Lack of ship motion coupling
Thermal modeling	Advanced CFD and analytical models	Limited experimental validation at scale
BOG utilization	Individual strategies explored	Poor integration with propulsion systems
Operational dynamics	Simplified steady-state assumptions	No transient, real voyage profiles

3.4. Safety and Risk Assessment of LH_2 Storage Systems

The safe integration of liquid hydrogen (LH_2) storage systems onboard ships represents a major barrier to the large-scale adoption of hydrogen-powered maritime transport. This challenge is mainly attributed to the unique physicochemical properties of hydrogen, such as low ignition energy, wide flammability range, high diffusivity, and rapid dispersion behavior [34]. Consequently, safety concerns have become a focal point of the nascent LH_2 maritime research.

Existing studies have investigated hydrogen leakage, dispersion, fire, and explosion in great detail, using computational fluid dynamics (CFD) simulations, quantitative risk assessment methods, and probabilistic safety models [4,11,62–80]. These approaches have significantly improved understanding of hydrogen behavior under accidental release conditions and have informed the development of preliminary hazard mitigation strategies. However, much of the available knowledge comes from land-based hydrogen applications, such as refuelling stations, industrial process facilities, and stationary storage systems [62,81–90]. Consequently, the direct applicability of these findings to maritime environments remains unclear. Ships, in contrast to land-based installations, are characterized by confined, compartmentalized spaces with complex ventilation pathways, continuously changing environmental conditions, and vessel dynamics that can strongly influence hydrogen behavior. While CFD-based studies have attempted to replicate hydrogen behavior in enclosed ship compartments [68,72,91–98], only limited experimental works have included the effects of ship motion and transient ventilation, despite their strong influence on dispersion behavior [99,100].

A recurring issue across the literature is the tendency to assess LH_2 storage systems as stand-alone systems rather than as integrated elements of the overall vessel design. Often, hazard zone analyses, ventilation assessments, and explosion consequence studies are performed without taking into account realistic ship arrangements and operational constraints. This often leads to poor representation of important interactions among storage tanks, structural barriers, machinery spaces, ventilation systems, and potential ignition sources [64,72,95]. This piecemeal approach leads to significant uncertainty in safety evaluations, resulting in either overly conservative design requirements or inadequate hazard mitigation measures.

These uncertainties are further exacerbated by the lack of large-scale experimental validation under maritime-relevant conditions. Most available validation studies are based on small-scale experiments or idealized scenarios, with very limited data from full-scale marine environments [68,101–103]. Thus, critical accident scenarios such as collision-induced tank rupture or grounding remain poorly understood. Moreover, existing risk models rarely include transient operational conditions such as variable loading conditions, bunkering procedures, boil-off gas management, and emergency shutdown operations, which are of importance for practical ship operations [11,95,104].

From a regulatory perspective, the literature also highlights a lack of comprehensive safety frameworks developed for LH_2-fueled ships. The existing guidelines are fragmented and largely derived from LNG carrier standards and conventional gas-handling regulations, which fail to comprehensively address the distinct hazards associated with cryogenic hydrogen systems [11,105,106]. Although the International Maritime Organization and other bodies are developing guidelines for alternative marine fuels, a harmonized international framework for LH_2 marine applications has not yet been finalized.

Overall, the literature indicates that while much progress has been made in understanding the risks associated with hydrogen at the component and process levels, the development of integrated safety methodologies for LH_2-powered vessels remains at an early stage. Future research will need to implement multidisciplinary approaches that combine hydrogen leak and dispersion modeling, structural safety analysis, ventilation design, operational risk assessment, and regulatory development within coherent ship-level safety frameworks. Large-scale experimental programs and real-world demonstration projects will also be critical to validating existing models and reducing uncertainty in practical maritime applications. Table 4 summarizes the identified knowledge gaps in LH_2 safety and risk assessment.

3.5. Regulatory Challenges of LH_2-Fueled Ships

The regulatory framework for liquid hydrogen (LH_2) in maritime transport is still in an early stage, reflecting the broader technological immaturity of hydrogen-fueled shipping compared with conventional and LNG-based systems. Demonstrator-oriented studies on LH_2 carriers constantly highlight that current maritime safety regimes are largely based on assumptions about hydrocarbon fuels, especially those derived from liquefied natural gas (LNG) operational experience [7,8,10,11]. While these frameworks provide a fundamental basis for cryogenic fuel handling, they are not directly applicable to hydrogen because of its significantly different physical properties (e.g., lower boiling point, wider flammability range, and higher diffusivity) [34,107]. This mismatch creates a regulatory gap where LH_2-specific risks are only partially covered by existing maritime safety codes.

At the international level, the International Maritime Organization has developed goal-based regulatory frameworks that provide high-level safety principles for alternative fuels; however, detailed prescriptive requirements for LH_2 systems are still evolving. Studies of early LH_2 ship design and approval processes show that, in practice, this forces designers to work in a hybrid regulatory environment of interim guidance documents, classification society rules, and project-specific risk assessments [10,11,105,108]. The resulting regulatory fragmentation leads to variability in design interpretation and creates uncertainty in certification pathways. A key element of this fragmentation is the lack of harmonized technical standards for critical aspects of LH_2 system integration, including tank placement, insulation performance criteria, controlled venting strategies, and emergency response protocols. Studies of shipboard LH_2 system design have consistently shown that classification societies often apply the safety logic of LNG systems to hydrogen systems in the absence of hydrogen-specific empirical benchmarks [7,8,15,34]. However, this analogy-based approach is increasingly recognized as limited, as hydrogen exhibits fundamentally different leakage dispersion behavior, ignition characteristics, and thermal radiation dynamics compared with methane-based fuels [109]. As a result, safety criteria based on LNG practice may not be representative of hydrogen-specific hazard evolution scenarios.

This lack of empirical basis, particularly for hydrogen, is closely linked to the limited operational experience with LH_2-fueled or LH_2-carrier vessels at commercial scale. Experimental and demonstrator studies show that current safety distances, hazard classifications, and operational constraints are based on numerical modeling or small-scale experiments rather than on full-scale maritime operations [110–113]. While these methods are essential for gaining insights at the early stages, they cannot address complex shipboard interactions such as confined-space dispersion, dynamic ventilation effects, or coupled thermo-structural responses under actual voyage conditions. Regulatory assumptions are therefore only partially tested, and long-term safety

Table 4
Identified knowledge gaps in safety and risk assessment.

Aspect	Current state of knowledge	Identified gap
Leak, dispersion & explosion	Well-studied (land-based)	Not validated for ship environments
Risk models	Established methods exist	Limited maritime-specific models
Experimental data	Small-scale tests	No large-scale maritime validation
Regulations	Emerging guidelines	No dedicated LH_2 maritime code

margins can be trusted only to a certain extent.

Finally, one structural limitation increasingly recognized in the regulatory landscape is the weak interaction between safety rules and the ship design process itself. Current regulations are typically incorporated as external constraints, after or in parallel with design development, rather than being embedded into early design optimization frameworks. Research on LH_2 ship system integration demonstrates that such a separation hinders the simultaneous optimization of safety, efficiency, and space utilization, resulting in a conservative design outcome that tends to over-emphasize compliance at the expense of performance [10,11,34]. An integrated design-regulation coupling approach, on the other hand, entails embedding regulatory constraints directly into multi-physics optimization frameworks. This approach may allow for more balanced solutions, but such methodology is largely undeveloped for LH_2 maritime systems.

Overall, the literature suggests that the regulatory environment for LH_2 shipping is still evolving and not yet mature enough to support large-scale deployment. Close coordination among industry stakeholders, research institutions, and regulatory bodies is therefore needed to develop standardized LH_2-specific rules based on validated operational data and full-scale demonstration projects. A summary of the regulatory and classification knowledge gaps for LH_2-shipping is presented in Table 5.

3.6. Operational and Lifecycle Considerations of LH_2-Fueled Ships

The operational and lifecycle performance of liquid hydrogen (LH_2)-fueled ships remains among the least mature domains in current maritime decarbonization research. Although considerable progress has been made in conceptual ship design and component-level engineering [15,26,30,111,114–116], current knowledge still does not suffice to characterize system behavior under real-world operating conditions over full-service lifecycles. In particular, current studies do not yet tightly couple critical interactions among fuel handling, onboard storage, propulsion demand, and long-term system degradation [9,89,117].

A central operational barrier lies in LH_2 bunkering, which requires cryogenic infrastructure, advanced thermal management, and stringent safety controls [118]. Although several proposals have been developed, most are derived from liquefied natural gas systems, or are still conceptual, and no generally accepted standardized procedures exist [104,119–122]. This lack of operational standardization is inherently linked to uncertainties in safety, boil-off management, and transfer efficiency, which can have a significant effect on system performance during realistic refuelling operations.

From a lifecycle perspective, uncertainties extend to material durability and system reliability. Over time, tank integrity, insulation performance, and the risk of leakage may be affected by repetitive thermal cycling, pressure fluctuations, environmental conditions, and mechanical loads [123,124]. Empirical data from long-term maritime applications are mostly missing. As a result, maintenance strategies, diagnostic methods, failure prediction and risk models, and inspection intervals are still considered speculative, especially for safety-critical cryogenic containment systems [122,125–127]. These technical uncertainties are exacerbated by the mismatch between modeling assumptions and operational reality. Many existing studies are based on steady-state or simplified voyage profiles that do not capture the dynamic variation of energy demand and the coupled behavior of propulsion systems and onboard hydrogen supply, including transient boil-off gas utilization. This limits the predictive capability of current system-level models [15,28,111,128–130].

There is also a lack of sufficient understanding of the full environmental and economic implications of LH_2 adoption in shipping from a broader sustainability perspective. Hydrogen is frequently described as a zero-emission energy carrier at the point of use. However, upstream processes – production, liquefaction, transport, and distribution – can significantly influence the overall environmental performance [131]. Moreover, integrated lifecycle assessments combining technical system performance with operational data are still scarce, limiting robust comparisons with other alternative fuels [30,132–137].

Generally, the current state of research reflects a fragmented understanding in which operational practice, system degradation, and lifecycle sustainability are usually studied in isolation rather than as an interconnected whole. This fragmentation underscores the need for long-term experimental datasets and coupled techno-operational models for the reliable deployment of LH_2 systems. Table 6 provides a summary of the key operational and lifecycle knowledge gaps in LH_2 shipping.

4. Research Roadmap for LH_2 Storage Integration

Based on the identified knowledge gaps, future research should prioritize the development of integrated system-level approaches to LH_2 ship design and operation. The short-term focus should be on improving the fidelity of current models by incorporating dynamic operating conditions, such as vessel motion and transient fuel demand. This includes coupling thermal models for boil-off gas generation with fuel supply systems and voyage profiles. In the medium term, experimental validation at pilot scale is required to bridge the gap between simulation and real-world application. This implies developing test beds and demonstration vessels that can generate operational data in real maritime conditions. These activities are critical to validate safety models, thermal performance, and system integration strategies. Long-term research should aim to develop holistic design frameworks that incorporate insights from cryogenic engineering, naval architecture, and safety engineering. Such frameworks should allow for the joint optimization of storage systems, ship layout, and operational strategies. The frameworks should be supported by digital tools such as system simulation and digital twins. Regulatory development must also keep pace with technological advances. Collaboration with organizations such as the International Maritime Organization will be critical to developing standardized guidelines and certification pathways for LH_2 systems. The successful uptake of LH_2 in maritime applications will ultimately depend on the convergence of technological innovation, experimental validation, and regulatory alignment. The research roadmap showing the short-, medium-, and long-term goals is illustrated in Fig. 3.

Table 5
Regulatory knowledge gaps.

Aspect	Current state of knowledge	Identified gap
IMO framework	General alternative fuel guidelines exist	No LH_2-specific code
Classification rules	Early-stage provisional rules	Lack of harmonization across societies
Design integration	Rules applied post-design	No integrated design-regulation framework
Safety standards	LNG-based analogies used	Inadequate LH_2-specific validation
Operational certification	Limited experience	No real-world LH_2 vessel data

Table 6
Operational and lifecycle knowledge gaps.

Aspect	Current state of knowledge	Identified gap
Bunkering	Conceptual procedures exist	No standardized LH_2 bunkering protocol
Lifecycle behavior	Limited simulation studies	No long-term operational data
Maintenance	General guidelines only	No LH_2-specific inspection standards
Environmental impact	Partial LCA studies	No integrated system-level assessment

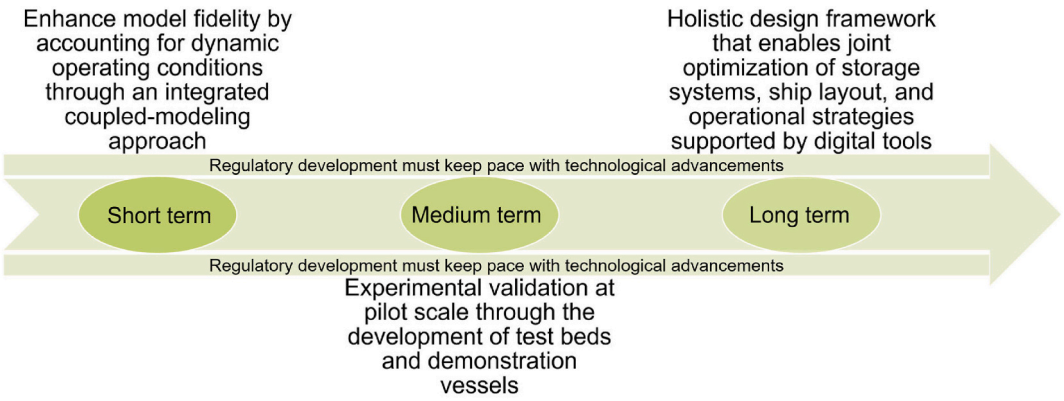


Fig. 3. Research roadmap for liquid hydrogen storage integration onboard vessels.

5. Conclusion

This review investigated the state of the art in liquid hydrogen (LH_2) storage integration for maritime applications, with emphasis on system-level interactions, technological limitations, and cross-disciplinary challenges. The study provided an integrated perspective on the development of LH_2 storage technologies and their interaction with ship design, operational requirements, and regulatory frameworks through a structured literature analysis and bibliometric mapping approach. The findings indicate that while significant progress has been made in the development of cryogenic storage technologies, insulation systems, and tank configurations, most of the current research is still focused on individual subsystems and not on fully integrated ship-level solutions. In particular, LH_2 storage is often regarded as a stand-alone engineering component, with limited consideration of its coupling with ship structural design, hydrodynamic behavior, and operational constraints.

An important finding in this review relates to the identification of strong thematic clustering in the literature analysed. However, weak connectivity was found between the identified clusters based on the results of the bibliometric analysis. This implies the lack of a systems-based approach across the research domains. Such fragmented knowledge means that while there has been substantial progress achieved at the component level, overall holistic approaches to ship design still need further work. In terms of technical challenges, there are unresolved issues of boil-off management, structural integrity in cryogenic conditions, and optimal tank placement within constrained ship geometries. On an operational level, there are issues related to the performance of LH_2 ships throughout their lifecycle, as well as maintenance strategies and fuel handling under real maritime conditions. Furthermore, the evolving regulatory framework for LH_2-fueled ships also poses an obstacle to their wider adoption. Overall, this review shows that LH_2 ship integration is a multi-disciplinary issue. Resolving this issue requires the development of coupled multi-physics models, operational data collected from demonstration projects, as well as dedicated regulatory frameworks for hydrogen-fueled ships.

Therefore, future research should focus on (i) system-level integration approaches that couple tank behavior with ship dynamics, (ii) long-term experimental and operational validation of LH_2 storage systems in maritime conditions, and (iii) harmonized international standards for safe and scalable deployment. Addressing these challenges will be essential to LH_2 transition from a promising alternative fuel to a viable solution for decarbonizing global shipping.

CRediT authorship contribution statement

Bright E. Okpeke: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lars Baetcke:** Writing – review & editing, Supervision. **Sören Ehlers:** Supervision.

Data Availability Statement

The bibliometric data used in this study were mostly obtained from Scopus and Web of Science Core Collection (Clarivate) under an institutional subscription. Redistribution of the raw records is not permitted due to licensing restrictions. However, the derived datasets and analysis files supporting the findings of this study are available from the corresponding author upon reasonable request.

Funding

No external funding was received for carrying out this research study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2026.158510.

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