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# Analysis of Experimental Studies from European Projects on the Safety of Liquefied Hydrogen Storage Tanks: Insights and Research Directions

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Abstract
Liquefied hydrogen ($LH_2$) is increasingly regarded as a promising energy carrier for decarbonizing transport due to its high energy density and zero carbon emissions at the point of use. In particular, the application of $LH_2$ in maritime systems requires large-scale cryogenic storage tanks, which introduce safety challenges that differ fundamentally from those of conventional marine fuels. Although numerous European projects have addressed $LH_2$ technologies, a structured synthesis of experimental safety knowledge relevant to shipboard $LH_2$ storage tanks is still lacking. This study systematically reviews European projects related to the safety of $LH_2$ storage, transfer, and operation, with the objective of identifying safety-relevant knowledge gaps that limit the risk-informed design and safe implementation of $LH_2$ storage tanks in maritime applications. The review primarily focuses on physical experiments investigating safety-critical phenomena, which are analyzed across key hazard domains, including $LH_2$ release and dispersion, pool formation and evaporation, ignition and explosion behavior, fire exposure, boiling liquid expanding vapour explosion (BLEVE), and mitigation technologies. In addition, selected non-experimental European projects are considered to provide system-level context and to support the interpretation of experimental findings within a risk-based safety framework. The cross-project analysis shows that most existing experiments are limited to static or quasi-static conditions, revealing a critical gap in experimental evidence for dynamic effects that are particularly relevant to large-scale $LH_2$ storage tanks in maritime environments. Based on the identified gaps, this study outlines key research directions to support risk-informed design and the safe maritime implementation of $LH_2$ storage tanks.

*Keywords*: Experimental studies, Liquefied hydrogen storage tanks, Safety, Research direction

## 1. Introduction

In 2023, the International Maritime Organization (IMO) announced its revised greenhouse gas (GHG) strategy, targeting net-zero emissions from international shipping by 2050. To reach this target, the IMO identified several mitigation pathways for reducing carbon dioxide emissions from maritime transport. According to the IMO strategy, fuel substitution represents the most effective measure, accounting for approximately 80–100% of the total emission reduction potential, compared to operational improvements or efficiency measure, as shown in Figure 1 (IMO, 2023).

Fig. 1.Wide variety economic solutions (IMO, 2023)

This underscores the need to replace conventional fossil fuels with carbon-free alternatives in maritime transport. Among various alternative fuels under consideration, such as methanol and ammonia, hydrogen has attracted particular attention due to its ability to generate energy through combustion or electrochemical conversion without emitting carbon-containing compounds at the point of use. In addition, hydrogen can be stored at significantly higher volumetric energy density in liquid form compared to its gaseous state, making liquefied hydrogen ($LH_2$) a promising option for long-distance transport and large-scale energy applications. (Abohamzeh et al., 2021; Aziz, 2021) As a result, research and development activities related to $LH_2$ storage, transfer, and utilization have intensified in recent years. The use of liquefied hydrogen as a marine fuel or cargo at large scale requires cryogenic storage tanks of substantial size, introducing safety challenges that differ fundamentally from those associated with conventional marine fuels. While several European demonstration projects have investigated the technical feasibility of $LH_2$ systems, regulatory frameworks, design codes, and safety guidelines for large-scale maritime $LH_2$ storage tanks remain insufficiently developed. In particular, internationally harmonized rules and risk-based design criteria are still lacking. Accordingly, the objective of this study is to identify experimentally grounded safety knowledge gaps that limit the risk-informed design and safe implementation of large-scale liquefied hydrogen storage tanks in maritime applications, with particular emphasis on their applicability under dynamic maritime operating environments. To achieve this objective, the study addresses the following research questions: (Q1) What safety-critical phenomena related to $LH_2$ storage have been experimentally investigated in European projects, and what are the scope and limitations of the available experimental evidence? (Q2) To what extent can existing experimental findings be applied to large-scale $LH_2$ storage tanks under maritime-relevant and dynamic conditions? (Q3) What key experimental gaps must be addressed to support reliable risk assessment and risk-informed design of $LH_2$ storage systems for maritime applications? The remainder of this paper is structured as follows. Section 2 presents an analysis of major European projects related to liquefied hydrogen safety, distinguishing between non-experimental and experimental approaches and examining their contributions to the understanding of $LH_2$ storage tanks safety. Section 3 synthesizes cross-project insights derived from the experimental evidence, discusses the applicability of existing findings to maritime $LH_2$ storage tanks, and identifies key knowledge gaps and future experimental research needs. Finally, Section 4 summarizes the main conclusions of the study.

## 2. Analysis of European projects

A total of twelve European projects related to the operation, transport, and storage of liquefied hydrogen were examined in this study. As shown in Figure 2, these projects are distributed across multiple European countries and often involve multinational consortia, reflecting a coordinated European effort to address safety challenges associated with large-scale $LH_2$ applications.

Fig. 2.Projects classification by country

The reviewed projects address liquefied hydrogen storage tanks using different research approaches, including numerical analyses, system-level studies, experimental investigations, and demonstration activities, depending on their objectives and maturity levels. In this study, the projects are classified according to whether physical experiments were conducted. Projects without physical experiments primarily rely on numerical simulations and risk-based analyses to support safety evaluation, whereas projects that include experimental campaigns provide empirical evidence relevant to hazard identification and risk assessment of liquefied hydrogen storage tanks. The experimental studies investigate safety-critical phenomena such as hydrogen release, dispersion, ignition, explosion, and fire exposure, with the resulting data often supporting the development of safety guidelines, technical recommendations, or pre-standardization activities. The analyzed projects include both completed and ongoing initiatives, taken together; they provide a representative overview of the current state of European research on $LH_2$ safety and form a consistent basis for identifying knowledge gaps and future research needs relevant to risk assessment.

### 2.1. *Projects without physical experiments*

Several European projects have addressed the safety of liquefied hydrogen systems without conducting dedicated physical experiments on release, ignition, or failure phenomena. Instead, these projects contribute to liquefied hydrogen safety through system-level demonstrations, numerical analyses, risk-based design approaches, and pre-standardization activities. Their primary role is to establish realistic operational scenarios, identify safety-relevant hazards, and support the development of regulatory and technical frameworks, thereby complementing experimental research. These non-experimental projects can be broadly grouped according to their primary safety contribution, including operational demonstration, conceptual system design, numerical hazard analysis, and preparatory modelling.

Operational demonstration projects, such as MF Hydra, provide important safety-related insights by integrating liquefied hydrogen storage tanks, fuel cell systems, and bunkering interfaces into real maritime environments (Østvik, 2021). Although no controlled safety experiments were performed, these projects rely on quantitative risk assessment and alternative design methodologies to address hazards associated with hydrogen leakage, accumulation, and explosion in confined shipboard spaces, thereby revealing practical challenges related to system integration, emergency venting, and regulatory compliance.

Conceptual design-focused projects address the operational safety of large-scale liquefied hydrogen infrastructure through system-level analyses. Projects such as $LH_2$ pioneer and DelHyVEHR investigate the behavior of $LH_2$ storage and transfer systems using thermodynamic analyses, process modelling, and integrated safety evaluations (Cirrone et al., 2023, 2025; Molkov et al., 2024). These studies examine key parameters influencing safe operation, such as boil-off gas management, pressure control, transfer stability, and operational procedures, which are directly relevant to risk assessment of large-capacity $LH_2$ storage and bunkering systems.

Numerical and analytical safety studies contribute to liquefied hydrogen safety by investigating hazard scenarios through modelling and simulation in cases where dedicated physical experiments are not available or feasible. Projects such as ALRIGH2T focus on system-level risk assessment of $LH_2$ refuelling concepts through structured hazard identification, digital twin modelling, and risk-based analyses, supporting the definition of safety requirements, operational procedures, and potential certification pathways (ALRIGH2T, 2024). In parallel, CFD-based hazard assessment project, including e-SHyIPS, apply high resolution numerical simulations to examine hydrogen dispersion, accumulation, and explosion behavior in confined environments representative of shipboard spaces (Luigi, 2022). These studies investigate the influence of leak location, ventilation efficiency, and compartment geometry on hazardous conditions, providing preliminary guidance for compartment layout, venting strategies, and mitigation measures. Although these numerical and analytical studies do not generate empirical data for direct model validation, they play a critical role in defining safety-relevant boundary conditions and representative accident scenarios. By bridging system-level safety concepts and detailed hazard physics, they support pre-standardization activities and inform risk-based design approaches for maritime hydrogen applications, thereby complementing experimental research.

Preparatory modelling project such as ESKHYMO, address safety-critical phenomena that are difficult to investigate experimentally at early stages, including cryogenic effects, accidental releases, and flammable cloud formation (Truchot & Chaumeix, 2023). By defining representative accident scenarios and guiding the design of future experimental campaigns, these projects help bridge the gap between conceptual safety analysis and experimental investigation.

Taken together, these non-experimental projects demonstrate that system-level and modelling-based research plays a critical role in contextualizing experimental findings. While they do not generate empirical data for direct model validation, they establish operational and safety-relevant boundary conditions that are essential for applying risk assessment methodologies to large-scale $LH_2$ storage and transport systems.

### 2.2.*Projects with physical experiments*

Several European and national projects have conducted physical experiments to investigate safety-relevant phenomena associated with liquefied hydrogen storage, transfer, and accidental release. These initiatives provide empirical data supporting hazard identification, consequence analysis, and model validation for risk assessment. The experiments cover a range of safety-critical phenomena relevant to $LH_2$ systems. The following subsections synthesize the experimental contributions by grouping projects according to the type of physical phenomena investigated, rather than by individual project.

#### 2.2.1.*Release, dispersion, and pool formation experiments*

Physical experiments on liquefied hydrogen release and dispersion form a major component of the experimental research landscape. Large-scale outdoor (Buttner et al., 2021) and semi-confined releases tests were conducted within the FFI and the PRESLHY project to investigate $LH_2$ outflow behavior, vaporization, and near- and far-field dispersion, as shown in Figure 3 (Aaneby et al., 2021).

Fig. 3.Dispersion tests (Simon Coldrick, 2023)

These experiments examined the influence of release orientation, pressure, nozzle size, and environmental conditions on hydrogen cloud formation and propagation. In several cases, transient pool formation was observed for downward releases, providing empirical evidence on liquid spreading, evaporation rates, and the formation of cold, dense hydrogen clouds near the ground. Complementary release and dispersion experiments were also performed within the ELVHYS project (Schiaroli et al., 2025; Simon Coldrick, 2023), focusing on controlled $LH_2$ releases under different ventilation conditions. These tests investigated hydrogen accumulation and dispersion in partially confined geometries, generating data relevant to hazard distances and ventilation effectiveness. Together, these experiments provide empirical input for evaluating release scenarios that are commonly considered in quantitative risk assessment of $LH_2$ storage and transfer systems.

#### 2.2.2.*Ignition and explosion experiments*

Ignition and explosion behavior of hydrogen resulting from liquefied hydrogen releases were investigated through a series of controlled experiments in FFI project, PRESLHY, ELVHYS and SH2IFT. These experiments addressed ignition likelihood, flame development, and overpressure generation under both open and confined conditions. In confined or semi-confined configurations, rapid hydrogen accumulation was observed following $LH_2$ releases, leading to severe explosion pressures upon ignition, depending on ventilation and enclosure geometry. Within the PRESLHY and ELVHYs projects, ignition-related experiments also examined electrostatic charging phenomena associated with cryogenic hydrogen releases. The results indicated that while sustained electrostatic ignition is unlikely, transient charge generation may occur under specific multiphase flow or ice-related conditions. The ELVHYS project further investigated controlled ignition and combustion behavior under varying congestion levels using dedicated ignition sources, as shown in Figure 4, providing quantitative data on flame propagation and explosion overpressure (Simon Coldrick, 2023). The SH2IFT project extended explosion research by conducting large-scale experiments in confined enclosures and transport-representative geometries, generating data on explosion dynamics relevant to large-scale hydrogen applications (Anders Ødegård et al., 2022).

Fig. 4.Combustion tests (Schiaroli et al., 2025)

### 2.2.3.*Fire exposure and BLEVE experiments*

Several projects investigated the response of liquefied hydrogen storage tanks to external fire exposure and catastrophic failure scenarios. The SH2IFT project conducted large-scale fire and boiling liquid expanding vapour explosion (BLEVE) experiments, as shown in Figure 5, on vacuum-insulated $LH_2$ vessels to assess vessel integrity, failure modes, and consequence severity under prolonged fire loading (Anders Ødegård et al., 2022). These experiments demonstrated that failure likelihood and consequences depend strongly on insulation type, vessel orientation, and pressure relief behavior. Within the ELVHYS project (Martin Kluge & Karim Habib, 2023), fire exposure experiments were performed on cryogenic transfer lines to examine pressure escalation and insulation degradation under localized fire loads.

Fig. 5.BLEVE test (Anders Ødegård et al., 2022)

These tests provided empirical evidence on heat transfer mechanisms and pressure build-up in vacuum-insulated piping systems, highlighting vulnerabilities that are relevant for risk assessment of $LH_2$ transfer operations. Together, these experiments address high-consequence, low-frequency scenarios that are critical for evaluating worst-case hazards in $LH_2$ systems.

### 2.2.4.*Mitigation and safety technology experiments*

Experimental research on mitigation technologies was primarily conducted within the STACY project, which focused on passive autocatalytic recombination as a means of reducing flammable hydrogen concentrations under cryogenic conditions (Tanaka et al., 2025). Laboratory-scale and medium-scale experiments were performed to evaluate catalyst performance at low temperatures, under oxygen-deficient conditions, and at high hydrogen concentrations. These tests provided empirical data on catalyst activity, robustness, and thermal behavior, supporting the feasibility of passive mitigation measures for $LH_2$ storage and transport applications. Although the mitigation experiments differ in nature from release or explosion tests, they address safety at the system level by evaluating technologies intended to limit hazard escalation following accidental releases. As such, they complement consequence-focused experiments by introducing preventive and mitigating safety functions into the overall risk framework.

### 2.2.5.*Experimental scope and limitations*

As shown in Table 1, the experimental projects reviewed provide a substantial body of empirical data on safety-relevant phenomena associated with liquefied hydrogen storage tanks. However, most experiments were conducted under static or quasi-static boundary conditions, with limited consideration of dynamic effects such as motion-induced sloshing, coupled thermal-hydraulic behavior, or long-term operational variability. As a result, while the experiments are directly applicable to hazard identification and consequence modelling, their applicability to large-scale maritime $LH_2$ storage tanks operating under realistic motion conditions remains limited.

Table 1. Hazard phenomenon for each project

| Hazard phenomenon | Projects |
|---|---|
| Release, dispersion, and pool formation | FFI, PRESLHY, ELVHYS |
| Ignition and explosion | FFI, PRESLHY, ELVHYS, SH2IFT |
| Fire exposure, BLEVE | SH2IFT, ELVHYS |
| Mitigation technologies | STACY |

## 3. Insights and research directions

The analysis of European projects presented in Section 2 provides a comprehensive overview of how liquefied hydrogen safety has been investigated through both experimental and non-experimental approaches. Taken together, these projects demonstrate substantial progress in understanding safety-relevant phenomena associated with $LH_2$ storage, transfer, and accidental release. At the same time, the analysis reveals several structural limitations that have important implications for risk assessment and for the future development of large-scale liquefied hydrogen storage tanks, particularly in maritime applications.

### 3.1.*Insights from cross-project analysis*

A key insight from the reviewed projects is that current experimental and analytical efforts predominantly address safety-critical phenomena under static or quasi-static boundary conditions. Most physical experiments focus on short-duration release, dispersion, ignition, explosion, and fire exposure scenarios in stationary configurations. These studies provide valuable empirical evidence for hazard identification and consequence modelling and have significantly improved the understanding of fundamental $LH_2$ behavior under controlled conditions.

In parallel, non-experimental projects have played an essential role in defining realistic operational scenarios, system architectures, and regulatory constraints. Through system-level demonstrations, numerical simulations, and risk-based design approaches, these projects have clarified how $LH_2$ technologies may be integrated into ships, refuelling infrastructure, and transport systems. Importantly, they highlight the complexity of $LH_2$ systems, where storage tanks, transfer lines, ventilation, and safety functions interact across multiple scales. However, when viewed collectively, the existing body of work reveals a clear imbalance between the level of experimental detail available for isolated phenomena and the level of system-level realism required for maritime risk assessment. While individual hazards have been extensively investigated, their combined effects under realistic operational conditions remain insufficiently explored.

### 3.2.*Maritime implications for $LH_2$ storage tanks*

The predominance of static experimental conditions represents a critical limitation when considering maritime liquefied hydrogen storage tanks. Ships operate under continuous multi-degree-of-freedom motions induced by waves, wind, and maneuvering, which can influence liquid sloshing, pressure evolution, structural loading, and boil-off behavior. These dynamic effects are not captured in most existing experiments and are only partially addressed in current modelling studies. From a safety perspective, this gap raises questions regarding the direct applicability of available experimental data to maritime scenarios. Consequence models derived from static experiments may not fully represent worst-case or credible accident scenarios on board ships, particularly for large-capacity $LH_2$ storage tanks. As a result, conservative assumptions are often required in quantitative risk assessments, potentially leading to overly restrictive design solutions or uncertainty in regulatory decision-making. The analysis also indicates that mitigation technologies, such as passive recombination or ventilation strategies, have primarily been evaluated under simplified conditions. Their effectiveness under coupled thermal, mechanical, and motion-induced effects remains largely unknown, limiting confidence in their performance as safety barriers in maritime environments.

### 3.3.*Research direction for risk-informed $LH_2$ storage tanks*

Based on these insights, future research on liquefied hydrogen safety should move beyond isolated and static configurations toward integrated and dynamic system investigations. Experiments that incorporate motion effects, long-duration operation, and realistic boundary conditions would provide critical data for validating consequence models and reducing uncertainty in maritime risk assessments. In parallel, advanced numerical modelling should be further developed to couple fluid dynamics, thermodynamics, and structural response under dynamic conditions. Such models can bridge the gap between laboratory-scale experiments and full-scale maritime applications, provided that they are supported by targeted experimental validation. From a regulatory perspective, the findings highlight the need for risk-based frameworks that explicitly account for uncertainties associated with limited experimental coverage. Insights from European projects can serve as a foundation for developing harmonized safety guidelines and design criteria, but additional evidence is required to support their application to large-scale maritime $LH_2$ storage tanks. Strengthening the link between experimental research, numerical modelling, and regulatory development will be essential for enabling the safe and reliable deployment of liquefied hydrogen in future maritime transport.

### 3.4.*Summary of key insights*

In summary, the reviewed European projects have significantly advanced the understanding of liquefied hydrogen safety through complementary experimental and non-experimental approaches. Nevertheless, important gaps remain with respect to dynamic effects, system-level interactions, and long-term operational conditions. Addressing these gaps through coordinated experimental, numerical analysis, and regulatory research represents a key step toward risk-informed design and safe implementation of large-scale $LH_2$ storage tanks in maritime applications.

## 4. Conclusions

This study reviewed European projects addressing the safety of $LH_2$ storage tanks, with the objective of identifying experimentally grounded safety knowledge gaps relevant to the risk-informed design and safe implementation of $LH_2$ storage systems in maritime applications. Both experimental and non-experimental projects were analyzed to provide a structured overview of how safety-critical phenomena related to $LH_2$ storage have been investigated.

The analysis shows that existing experimental research has generated valuable empirical data on key hazard phenomena, including $LH_2$ release and dispersion, ignition and explosion behavior, fire exposure, BLEVE, and mitigation technologies. These experiments provide an important basis for hazard identification and consequence modelling under controlled conditions. At the same time, non-experimental projects contribute system-level insights through numerical analyses, risk-based design approaches, and operational demonstrations, supporting the interpretation of experimental results within broader safety and regulatory frameworks.

However, the cross-project analysis also highlights a key limitation in the current evidence base. Most available experimental studies have been conducted under static or quasi-static boundary conditions, whereas large-scale maritime $LH_2$ storage tanks operate under dynamic environments involving ship motions, coupled thermal-hydraulic behavior, and long-term operational variability. Consequently, while existing experimental findings are directly applicable to hazard identification and consequence modelling, their applicability to realistic maritime operating conditions remains limited.

Accordingly, this study identifies the lack of experimental evidence addressing dynamic effects, system-level interactions, and long-duration operation as critical research gaps for maritime $LH_2$ storage safety. Addressing these gaps through future research that integrates dynamic experimental investigations with system-level analysis will be essential for reducing uncertainty in risk assessment and enabling the safe deployment of liquefied hydrogen storage systems in maritime transport.

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