Position Paper

Hydrogen Europe Research

Development of IGF Code for hydrogen

Providing comprehensive scientifically based safety recommendations for maritime applications

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Abstract

The decarbonisation of the maritime sector requires a transition to hydrogen as a clean fuel, yet the absence of a comprehensive regulatory framework remains a major barrier. The International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code), originally developed for liquefied natural gas, provides only limited "alternative design" provisions for hydrogen that are insufficient to address its specific hazards. Key risks, including high flammability, rapid dispersion, embrittlement effects and boil-off from cryogenic storage, need hydrogen-specific safety principles, including new paradigms and new engineering solutions, in some instances. The IGF Code requires revision of its goals and provisions to cover hydrogen's buoyancy, storage enclosures, redundancy systems and fuel cell applications. This position paper identifies the critical knowledge gaps and technological bottlenecks that hinder the development of scientifically based regulations, codes, and standards (RCS) for hydrogen-fuelled vessels. Fundamental research is urgently required to advance ventilation strategies, safe storage concepts, fire and explosion prevention, and inherently safer technologies such as self-venting tanks. Additional challenges include bunkering protocols, under-deck storage safety, double-walled piping integrity, and zero boil-off solutions for liquid hydrogen. The efforts by classification societies (DNV, LR, ABS) and EU projects (e-SHyIPS, HyShip, FLAG-SHIPS and more) represent important milestones, yet they are still fragmented and not fully prepared for global adoption. Absence of a common shared understanding of the alternative design process among stakeholders, can possibly force each project team to "repeat baseline safety assessments" and increase costs and slow a regulatory approval. A coordinated international research programme is needed to underpin the development of hydrogen provisions within the IGF Code, elevate key technologies to TRL 4–6, and support the safe, efficient, and cost-effective deployment of hydrogen in maritime applications. Achieving this will strengthen public trust, accelerate decarbonisation, and ensure Europe's leadership in clean maritime transport.

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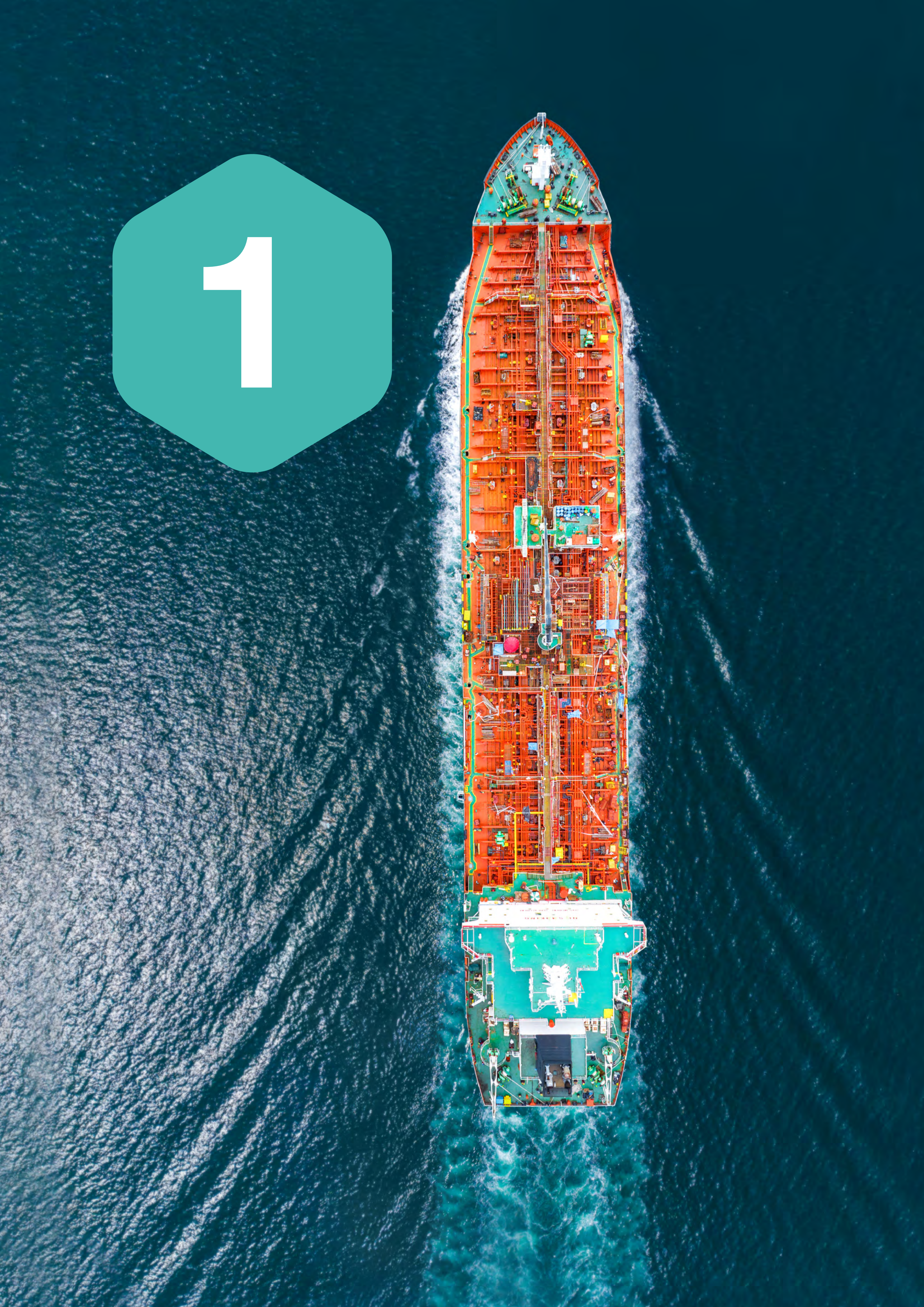
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Introduction

Fundamental research is essential to support pre-normative work that shapes international regulations, codes, and standards (RCS) in fast-evolving industries. In the maritime sector, current safety RCS lag behind industrial needs. The IGF Code permits “alternative design” for hydrogen, which requires equivalent functional safety, but this is a concept rather than practical guidance. Significant knowledge gaps and technological bottlenecks in hydrogen safety engineering must be addressed before effective adoption. The lack of hydrogen-specific provisions in the IGF Code hinders both safety and the wider deployment of hydrogen-powered vessels, despite urgent decarbonisation demands.

This topic highlights the importance of fundamental research that should underpin the development by RCS of the International Maritime Organization (IMO)[1]. To enable the safe and efficient adoption of hydrogen as a maritime fuel, a dedicated regulatory framework tailored to hydrogen-specific hazards and associated risks, and breakthrough safety technologies and innovative engineering solutions are urgently required.

This position paper aims to inform decision-makers and funders about the critical challenges in deploying inherently safer maritime applications, due to the gap in regulatory coverage under the IGF Code for hydrogen. The scope of the paper is to highlight the need to close existing knowledge gaps and technological bottlenecks through fundamental research. The IGF Code, designed for LNG, must be revised to address hydrogen-specific risks. Key hazards include high flammability, permeability, embrittlement, and buoyancy, which demand improved ventilation, leak prevention, and safety zones. Provisions are also needed for fuel cells, redundancy systems, storage, and fuel quality, drawing on land-based standards. Fire suppression, explosion prevention and emergency shutdown protocols must be adapted to hydrogen’s unique properties. There is a need for a comprehensive update of the IGF Code to integrate hydrogen-specific design, operational, and safety standards[2].

It is essential to meet all stakeholders’ expectations for the safety of hydrogen-fuelled ships, to build public trust and support the deployment of hydrogen technologies in the maritime sector. There is no thorough, shared understanding among stakeholders, including hydrogen-powered vessel designers, about the scope of the alternative design approval process. This makes regulatory approval difficult and demands significant investment as each time a new project team must “.a new project team could undertake redundant development, without added value”. Behind these difficulties are numerous knowledge gaps, e.g. on design of ventilation systems, hydrogen storage enclosures, use of other hydrogen systems under deck, etc. Fragmenting safety research across different projects to save costs has proven ineffective. To address this, the full spectrum of stakeholders should be brought together.

Several critical research gaps must be addressed for the safe deployment of hydrogen technologies in maritime applications. Firstly, ventilation systems with complex duct geometries need a dedicated investigation. An improper design can lead to hazardous accumulation of hydrogen, in the event of a release. Further research is also required to identify and qualify materials for hydrogen technologies, such as those used in fuel cells, that are suitable for harsh maritime environments.

Secondly, safety gaps include the need for strategies to manage emergency hydrogen releases and better understanding of jet fire and unignited release behaviour. Research must address thermal and pressure effects from delayed ignition and the deflagration-to-detonation transition (DDT) in non-uniform hydrogen-air mixtures, with thresholds defined for shipboard scenarios. Storage enclosures must be protected against incidental jet fires, and the risk of tank rupture in any fire must be eliminated. This is now achievable with self-venting tank technology, validated across fire intensities from spill fires to extreme impinging jet flames.

Lastly, systemic and operational challenges increase due to the existence of hydrogen systems using compressed gaseous hydrogen (CGH2) and liquid hydrogen (LH2). This includes the need for comprehensive safety provisions covering both shore-based and offshore operations, such as bunkering procedures, ship-to-shore interfaces and debunkering procedures.


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Current State of Research

Due to the lack of detailed hydrogen safety guidelines from the IMO, classification societies have independently established regulatory frameworks for hydrogen storage on vessels. Particularly, Lloyd's Register (LR) introduced the first set of classification rules for hydrogen fuel in 2023[3], outlining specific technical and safety requirements for ships utilising hydrogen as a fuel source. The regulations serve to bridge the existing gap in the IMO's current IGF Code. Also, Det Norske Veritas (DNV) published the first set of classification rules for hydrogen fuel in July 2024[4]. The Maritime Technologies Forum report[5] examines the viability of hydrogen as a zero-emission fuel in alignment with the IMO's strategy for the reduction of GHG emissions from ships by 2050. The report highlights the limited operational experience within the maritime sector regarding hydrogen as both cargo and fuel, while also recognising the increased safety risks associated with its application as a fuel compared to LNG. The IMO has been developing guidelines for the safe design of hydrogen-fuelled ships, with the guidelines to be presented by Sub-Committee on Carriage of Cargoes and Containers (CCC) [6]. The publication of guidelines is targeted for 2025[7] and the Interim Guidelines for the Safety of Ships Using Ammonia as Fuel developed by the CCC Sub-Committee, were issued by the IMO [8], marking a regulatory milestone providing goal-based, non-mandatory provisions (aligned with the IGF Code and SOLAS) to support the uptake of ammonia-fuelled ships.

More provisions to IGF Code related to hydrogen are also targeted to be introduced by the correspondence group in 2025. However, more joint efforts at the international level are required, including researchers and experts who specialise professionally in hydrogen safety. A Comité Européen de Normalisation (CEN) workshop Agreement (CWA) was achieved in 2024 on developing guidelines for integrating hydrogen propulsion systems based on fuel cells into passenger ships from the early design stages[9]. These recommendations aim to assist in risk assessments by utilising existing standards and are based on findings from the EU e-SHyIPS project [10]. The project developed guidelines for integrating hydrogen technologies into maritime passenger transport. It involved vessel redesigns to assess the feasibility of gaseous and liquid hydrogen propulsion, supported by hydrostatic/hydrodynamic analyses and CFD simulations of gas dispersion and explosion scenarios. Experimental work validated fuel cell components through inclination, materials and corrosion testing. The project also proposed bunkering strategies, conducted risk assessments, and identified gaps in the IGF Code, leading to preliminary recommendations for regulatory adaptation.

Unlike the IGF Code, the American Bureau of Shipping (ABS) Guide for Fuel Cell Power Systems for Marine and Offshore Applications[11] explicitly addresses hydrogen, yet its provisions largely reference the IGF Code. The DNV Handbook[12] includes hydrogen storage onboard. CGH2 at 70 MPa is more technologically mature but has a lower energy density compared to LH2, requiring larger storage volumes. LH2 offers a higher energy density, making it more suitable for long-haul applications. However, its liquefaction process is energy-intensive, it requires advanced insulation to minimise boil-off losses (which can be as high as 1~5% per day[13]), and it poses additional safety concerns related to extremely low temperatures.

Proper, scientifically based guidelines for ventilation systems and inherently safer technologies are crucial to prevent the accumulation of flammable hydrogen-air clouds. The safety principles for hydrogen fuel supply systems are outlined in the published DNV class rules for the use of hydrogen as fuel onboard ships[14]. These rules emphasise that ventilation of hazardous enclosed spaces should not serve as the primary safety barrier. Instead, the primary objective should be the prevention of a flammable atmosphere, thereby mitigating the risk of fire or explosion at its source. This can be achieved through the implementation of inerting or vacuum-insulated containment strategies, depending on whether the system utilises compressed gaseous or liquefied hydrogen.

Hydrogen ventilation is one of the most critical safety challenges in in maritime applications. Ventilation systems that are not properly designed may cause ignition and catastrophic explosions. A Risk-based approach is being adopted to tackle this, e.g. the ongoing revision of DNV's Handbook for Hydrogen Fuelled Vessels, which applies computational fluid dynamics (CFD) analyses and quantitative risk assessment (QRA) to develop design criteria for ventilation and fire safety. Contemporary multiphase CFD tools now allow simulations of ventilation interacting with fire suppression or unignited releases, however, they demand experimental validation on realistic vessel configurations. Full-scale experiments, e.g. those carried out by DNV[15], are important to establish detonation thresholds and support the development and refinement of the models. Such experiments also inform the integration of storage systems with leak and explosion assessments to ensure that there is no further incident escalation. Results can provide the scientific basis for regulatory approval.

To eliminate hazards and associated risks of compressed hydrogen storage systems (CHSS) rupture and potential catastrophic consequences, the innovative solution, such as explosion free in any fire self-venting tanks[16,17,18], can be used. These innovative solutions can remove previously applied expensive measures such as blast wave panels and explosion-proof enclosures.

Due to its cryogenic nature, LH2 storage requires maintaining extremely low temperatures to minimise boil-off losses. Ongoing research has identified several engineering approaches to manage boil-off[19,20,21], such as improved insulation and pressure control techniques. One promising concept is helium refrigeration for reducing losses through advanced thermal control. However, these approaches require further validation in maritime conditions.

Hydrogen bunkering research, including full-system simulations of hydrogen refuelling stations (HRS) for CGH2[22] and LH2[23] should address transparent and inherently safer bunkering protocols. The protocols must address the regulated limits for bunkering parameters and develop recommendations on reduction of temperature non-uniformity for CGH2[24]. The currently developed and validated modelling tools enable the design of detailed bunkering protocols, considering onboard storage conditions (residual pressure, hydrogen temperature, tank properties), bunkering system components (piping, valves, precooling, dispensers), and onshore storage parameters (pressure, volume, number of tanks).

Key achievements and milestones

As described above, the IMO is advancing safety guidelines for the use of hydrogen as a marine fuel. However, numerous knowledge gaps and technological bottlenecks remain, these should first be addressed through fundamental research to formulate new norms and guidelines. Nonetheless, the maritime industry has achieved meaningful milestones in the use of hydrogen technologies, demonstrating its commitment to zero-emission solutions. Norway introduced the MF Hydra[25], the world's first liquid hydrogen-powered ferry, classed by DNV. Equipped with two 200 kW fuel cells, it demonstrates the possibility of hydrogen propulsion in maritime transport; and there are more known cases of developed maritime transport powered by hydrogen. By 2024, the Antwerp/Flanders Port Training Center provided maritime education to more than 20000 trainees covering topics such as green hydrogen applications[26]. This effort shows the role of knowledge sharing in enhancing hydrogen. In parallel, Japan launched HydroBingo [27], which a hydrogen-powered passenger ferry with similar technological advancements and reinforcing global journey toward hydrogen adoption in maritime transport. In 2025 HD Korea Shipbuilding & Offshore obtained Approval in Principle from DNV for its pioneering vacuum-insulated large-capacity LH_2 tank technology[28]. This is an advancement on resolving the difficulties of expanding hydrogen storage for maritime applications, their safety and efficiency.

The tangible ongoing work contributing to development of technical requirements to the ship design, safe hydrogen handling and the use of hydrogen as fuel for power generation on board ships, is reflected in the rules and guidelines introduced by classification societies (LR, Bureau Veritas[29] etc). DNV has been proactive in establishing frameworks for the safe implementation of hydrogen in maritime applications. In 2021, DNV published the "Handbook for Hydrogen-fuelled Vessels," which offers a roadmap towards safe hydrogen operations using fuel cells. This handbook details how to navigate the complex requirements for design and construction and covers critical aspects of safety and risk mitigation, engineering details for CHSS, and implementation phases for maritime applications. However, it does not provide specific guidance for the onboard storage of CGH2, cryo-compressed hydrogen (CcH2), or LH2. Current DNV ventilation regulations do not account for the pressure peaking phenomenon (PPP), a critical safety phenomenon characteristic only of hydrogen[30], but describe this from gas inerting point of view, whereby the procedure needs to be designed using CFD. There is a lack of understanding around the hazards and associated risks related to explosions (deflagrations, detonations, storage tank rupture). For example, the standard by National Fire Protection Association, NFPA 2, referenced in DNV Handbook, only considers hydrogen jet flames and does not assess explosion hazards and risks.

There are also recommendations[31] for IGF Code, whereby it should be expanded to explicitly address hydrogen safety, with new chapters covering storage, energy conversion, and safety protocols. Ship-specific risk assessments must be developed, incorporating lessons from land-based hydrogen regulations. CFD simulations should be used to assess ventilation, gas dispersion, and explosion risks. Collaboration between maritime authorities, classification societies, and industry stakeholders is essential to establish comprehensive international guidelines. Implementing these measures will ensure the safe adoption of hydrogen in shipping, supporting global decarbonisation goals.

The development of self-venting tanks represents a key milestone in advancing inherently safer hydrogen storage in maritime transport and infrastructure. Such innovative tanks indeed are a breakthrough in fire safety by preventing storage rupture during exposure to fires. Their design can eliminate the main causes of catastrophic consequences, e.g. blast waves, projectiles or long flames triggered by a thermally activated pressure relief device (TPRD), while still allowing for hydrogen release under extreme conditions. This represents a paradigm shift in risk mitigation for hydrogen storage systems, both onboard and onshore.

Hydrogen leakage, dispersion and possible accumulation in enclosures pose very serious challenges for the design of effective ventilation systems. These can be intensified by dynamic marine conditions, including vessel motion and external weather effects that can influence hydrogen flow and potentially ventilation performance. Understanding the behaviour of hydrogen under these conditions requires advanced CFD modelling to design practical engineering solutions, especially when it comes to enclosures or during releases from vent stacks. Under-deck storage configurations need proper, robust ventilation integration to prevent hazardous accumulation and reduce the risk of ignition. The IGF Code and IGC Code specify a minimum of 30 air changes per hour (ACH), but this value is not based on scenario-specific consequence modelling. The further research is needed to determine optimal ACH values for a range of realistic hydrogen release rates and system configurations. The configuration and grouping of vent ducts and stacks must be optimised through fundamental studies and simulation-based design. The work on inherently safer CGH2 storage for maritime applications should include material-focused studies to confirm long-term integrity, performance under varying marine conditions and integration with ship specific ventilation and containment systems. Advancing this technology to a higher TRL requires coordinated experimental and numerical investigations well aligned with real-world maritime applications. To achieve long-term safety and operational efficiency, further fundamental research is required into zero boil-off technologies for LH2 storage, where helium refrigeration is a leading candidate. This research must address technical feasibility, integration into vessel systems and performance under variable marine conditions. Bunkering operations have additional challenges that require development of inherently safer and standardised protocols. These efforts across conceptual design, numerical simulation and experimental validation are important to elevate the technologies to higher TRLs and support their wider adoption in maritime applications.

Notable projects:

- FCH2 JU. e-SHyIPS: Ecosystemic knowledge in Standards for Hydrogen Implementation on Passenger Ship (101007226) [32].
- FCH2 JU. HyShip: Demonstrating Liquid Hydrogen for The Maritime Sector (101007205).
- FCH2 JU. FLAGSHIPS (826215) [33].
- FCH2 JU. MARANDA: Marine Application of a New Fuel Cell Powertrain Validated in Demanding Arctic Conditions. (735717) [34].
- FCH2 JU. H2PORTS: Implementing Fuel Cells and Hydrogen Technologies in Ports. (826246) [35].
- Horizon 2020. HySeas III. (769417) [36].
- Interreg Atlantic Area. HYLANTIC Atlantic Network for Renewable Generation and Supply of Hydrogen to promote High Energy Efficiency (EAPA_204/2016) [37].
- Innovate UK. Clean Maritime Demonstration Competition Round 1 (CMDC1): “Northern Ireland Green Seas” (10009311).
- Innovate UK. Clean Maritime Demonstration Competition Round 2 (CMDC2): “Hydrogen Fuel Cell Range Extender” (10041047).
- UKRI, EPSRC. UK National Clean Maritime Research Hub (MaRes) (EP/Y024605/1) [38].
- Norwegian Research Council. H2Maritime: H2Maritime Project.
- U.S. EERE. MarFC: Maritime Hydrogen Fuel Cell Project [39].
- California Air Resources Board. LCTI: Zero-Emission Hydrogen Ferry Demonstration [40].


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H2

Research Challenges

One of the key challenges is the design of ventilation systems for scenarios from permeation and allowed standard leak rates for connections to more challenging to tackle incidents with loss of containment, particularly in the context of under-deck storage and fuel piping. The fundamental research should investigate different scenarios of hydrogen leaks/release. This includes but is not limited to: releases inside, below-deck, where hydrogen can be trapped in “pockets”; transition to vent stack, outside releases from masts/ducts, and dispersion, including the cases when a marine vessel experiences heave or pitching and rolling. The latter could be challenging due to vessel motions, potentially leading to a flammable concentration entering the ventilation system or adjacent compartments with ignition sources. The weather conditions, e.g. wind gusts, could affect the ventilation efficiency and hydrogen dispersion.

Hydrogen releases from piping or pressure relief devices can ignite via electrostatic discharge, causing jet fires and explosion hazards. In confined or poorly ventilated spaces, ignition may lead to deflagration or even DDT, depending on enclosure size, pressure, and ventilation. Understanding these dynamics is crucial for effective mitigation. Numerical simulations can assess ventilation and fire suppression but require validation through full-scale testing. However, large-scale hydrogen explosion experiments are limited due to potential destruction. Combining full-scale experiments with modelling improves predictive accuracy, particularly for ventilation-fire suppression interactions, enhancing mitigation strategies and hydrogen safety.

For CGH2 tanks placed in compartments beneath the deck, an alternative safety measure involves inerting the entire hold space surrounding the CHSS. This approach could effectively suppress reactive conditions, thereby mitigating potential hazards. Fundamental studies would help understand hydrogen combustion in low-oxygen atmosphere that would underpin development inert gas filling strategies and formulate quantitative recommendations.

The design of large-scale LH2 storage tanks remains a work in progress, necessitating improved insulation and safer transfer systems. Both CGH2 and LH2 systems demand double-walled piping and robust venting systems to detect a leak and mitigate pressure build-up and accidental leaks. The design of the piping plays an important role in the safety of the entire system. A detailed study of combustion dynamics within double-walled piping systems is essential for provision of this piping integrity. Establishing the minimum structural strength required for the outer tubing to maintain gas-tight integrity and exploring strategies to contain explosion propagation within vent stacks are necessary. Understanding the conditions under which deflagration transitions to detonation is crucial for determining appropriate design pressures for secondary containment barriers.

One of the primary safety concerns associated with LH2 storage tanks is hydrogen boil-off. While leakage can be negligible due to the necessity of maintaining a vacuum within the double-walled tank structure, boil-off hydrogen can escape through the valve system. Mitigating or eliminating boil-off is essential not only to enhance cost-effectiveness, operational efficiency, and the vessel sailing range but also to address safety risks, particularly in confined storage environments such as under-deck compartments. There should be a design that could decrease heat flux from the surroundings, hence fundamental research on achieving a zero boil off must be undertaken. This could involve the use of a helium refrigeration, which should be studied numerically and validated experimentally.

The bunkering of onboard storage systems presents significant economic and safety challenges. The future research should tackle hydrogen temperature non-uniformity and novel approaches to pressure ramps that could underpin establishing standardised protocols that enhance the intrinsic safety and operational efficiency of the bunkering process while optimising time efficiency.

This position paper elucidates and stresses the need to undertake fundamental research, one of the objectives of which is identification and critical analyse of knowledge, technology, and regulatory gaps, including limitations of ventilation, bunkering, handling unignited and ignited releases in confined spaces and safety of under-deck hydrogen storage, prevention and mitigation of pressure and thermal effects in unscheduled conditions. The future research should also aim to support a standardised risk analysis framework to underpin the design and approval of novel solutions. Such framework would serve as a robust decision-support tool, demonstrating that proposed solutions comply with risk acceptance criteria in the current regulatory and operational context before the establishment of more standardised alternatives.

Activities are expected to achieve TRL between 4 and 6 by the end of research.

The proposed timeline for this topic is medium-term 3 years. The suggested estimate of the funding is €5M.


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Rationale for Advancing Research in This Area & Potential Applications

Whilst maritime shipping is critical to the European economy and one of the most energy-efficient forms of transport, it is also a significant and growing contributor to atmospheric greenhouse gases. The ambition of this research is in line with the European Green Deal[41] including "Fit to 55" package[42], which aim to address the barriers to decarbonisation of the maritime sector. The research will strengthen Europe's leadership in decarbonising waterborne transport and stimulate its transition to green energy through elaborated decision-making procedures for the selection of an appropriate alternative fuel for a particular maritime application.

The research will aid to address key technical and economic barriers to decarbonisation in the shipping sector by improving the safety, feasibility, and public acceptance of hydrogen as a maritime fuel. It will enhance understanding of hydrogen behaviour, mitigating perceived hazards and promoting broader social acceptance of hydrogen powered maritime sector. Inherently safer hydrogen technologies will not only reduce pollutants such as NOx but also establish new markets for hydrogen-compatible construction materials and material testing, supported by potential amendments to maritime RCS.

The research outcomes will strengthen the European economy and its leadership in the area. This advancement would position Europe ahead of competitors by achieving an unprecedented level of safety and cost reduction. Establishing a robust technological foundation, a skilled workforce, and the capability to manufacture competitive commercial products would drive global demand and market adoption. The potential for the impact of this research is non-doubtful, as it aligns with the European industrial strategy, namely supporting clean hydrogen[43] and ambitions of CHP[44]. The key findings will be influential in shaping policy, aligning with the objectives of HER[45]. The findings of a low-TRL research will extend beyond maritime applications, with potential spill-over benefits for other hydrogen-powered heavy-duty transport sectors. By addressing fundamental challenges, this work will contribute to the broader adoption of hydrogen as a clean energy solution in transport and beyond.

Overview of applications

This research will support the decarbonisation of maritime-related industries dependent on hydrogen storage, particularly maritime applications such as hydrogen-powered maritime vessels and transport applications (e.g. cargo ships, bulk carriers, ferries, passenger vessels, tugboats etc.) and port equipment (e.g. hydrogen fuel cell forklifts, terminal tractors, yard trucks etc.). Additionally, it will benefit stationary applications such as HRS for maritime vessels and onshore power supply systems.

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