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TransH2

TransH2

D.2.2.2 - Report on optimal configuration for 2 different hydrogen fuelled passenger vessels

Deliverable 2.2.2

Responsible partner: Navalprogetti Srl

Involved partners: PFRI, mareFVG, START, UNITS

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Notes:

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2 Project Overview

The assessment of the Interreg ITA-CRO program area identifies a considerable presence of ports along the Adriatic coast and highlights the critical need to advance the sustainability of port infrastructures. This will be achieved by adopting low-carbon transportation and mobility solutions, particularly through the modernization and sustainability of cross-border (CB) maritime connections. The primary goal of the TransH2 project is to improve sustainable crossborder sea mobility by showcasing viable applications of zero-emission fuels, such as green hydrogen, in maritime transport routes. This involves the introduction of these innovations to port authorities, transport operators, and stakeholders across the region.

The initiative aims to transition cross-border maritime transport towards sustainability by demonstrating the feasibility of innovative solutions and drafting detailed investment plans. This commitment will support the increase in the use of zero-emission fuels by 2050, aligning with the European Green Deal's objective to cut maritime sector emissions by 90%. It directly contributes to the EU's mission to "Restore our Ocean and Waters" by aiming for zero pollution and reduced greenhouse gas emissions in EU waters.

To support the Italian and Croatian economies through a complete hydrogen supply chain in maritime transport, the project emphasizes the need for further research and innovation. It focuses on developing hydrogen-powered vessels and the necessary refueling infrastructure in ports, aiming to meet the European Sustainable and Smart Mobility Strategy's 2030 target for market-ready zero-emission vessels.

Key activities include researching and analyzing options for greening maritime transport links, developing hydrogen-powered solutions for cross-border and local passenger transport. The project will also conduct feasibility studies for pilot areas on introducing hydrogen refueling stations in ports.

The adoption of new technologies presents a unique opportunity for the regions to address environmental challenges and enhance the safety, cleanliness, and efficiency of transport. This endeavour requires cross-border cooperation and the exchange of knowledge in developing and promoting sustainable sea mobility solutions.

However, deploying hydrogen in maritime transport faces significant challenges that demand collective efforts from both the private and public sectors in terms of investment, supportive regulatory and safety frameworks, ongoing research, innovation, and the establishment of a refueling infrastructure network in ports.

3 Activity 2.2 Overview

3.1 Objective

The Activity 2.2 – *Joint research and development of conceptual design on innovative concepts for hydrogen fuelled passenger ships for local and cross-border maritime traffic* focuses on the collaborative research and development of conceptual designs for two passenger vessels for regional and cross-border connections in the Adriatic Sea. The vessels will incorporate hydrogen propulsion. The conceptual design will address critical technical, regulatory, and economic aspects, integrating innovative solutions for sustainable maritime mobility.

The project will facilitate cross-border collaboration, with partners PFRI, mareFVG, NAVPRO, START, and UNITS working together on design co-creation. Additionally, an Independent Evaluation Expert will conduct a mid-term review (D.2.2.1) and a later assessment (D.3.3.1) to measure project progress, risk factors, and overall impact.

3.2 Scope of work

Building upon insights from Activity 2.1, the Activity 2.2 will explore optimal machinery configurations in terms of hydrogen storage technology and energy conversion technology. Key elements of the design process include:

- Review of the state of the art, applicable local regulations, and operational requirements.
- General arrangement plan to define ship layout and spatial organization.
- Technical specifications, including stability evaluations, power predictions, and an energy balance analysis.
- Preliminary electrical system design and bunker station arrangement for safe hydrogen refueling.
- Hazardous area planning and emergency shut-down philosophy for safety compliance.
- Economic feasibility assessment, including CAPEX and OPEX estimations.
- 3D modelling and visual materials to support design validation.
- Stakeholder engagement and collaborative peer review, ensuring cross-border knowledge exchange.
- Targeted communication activities, such as infographics, video clips, and social media outreach, to raise awareness of hydrogen-based maritime solutions.

3.3 Deliverable 2.2.2 – Report on optimal configuration for 2 different hydrogen fuelled passenger vessels

A critical outcome of this activity is Deliverable D.2.2.2, which will provide a detailed report on the process adopted for the identification of the optimal configuration for the two hydrogen-fuelled passenger ships that will operate on the two routes identified in A2.1. The document will serve as a starting point for the hydrogen system design that will be developed in the upcoming project period.

4 Executive Summary

This report presents an in-depth analysis of the optimal configuration for hydrogen-fueled passenger ships, synthesizing research findings, technical assessments, and peer-reviewed insights.

As maritime transport faces increasing pressure to decarbonize, hydrogen emerges as a promising zero-emission alternative, offering a clean and sustainable energy source for ferry operations. The document explores key technical aspects, including the most effective machinery setups, propulsion architectures, and energy system layouts. It provides a comparative analysis of various hydrogen storage technologies and energy conversion technology, evaluating their feasibility in terms of energy efficiency, operational practicality, and environmental impact.

A critical component of this study is the multicriteria assessment, which examines various hydrogen-powered vessel configurations against key performance indicators such as storage energy density, energy conversion system efficiency, storage costs, etc. Special attention is given to regulatory frameworks and safety considerations, ensuring that the proposed configurations align with international maritime safety standards.

From the multicriteria analysis **PEM Fuel Cell systems with compressed hydrogen storage** receive the highest ranking, driven by their superior energy efficiency, zero-emission operation, safety considerations, market readiness and alignment with IMO decarbonization goals. **This setup, featuring compressed hydrogen storage and a PEM fuel cell, will be applied to both vessels operating on regional and international routes.** The difference, as already highlighted in Activity 2.1, lies in the ship's endurance when operating with hydrogen. The vessel concept for regional routes will consider a fully hydrogen-powered vessel, while for international routes, the design will adopt a hybrid solution, with hydrogen used only during port operations.

The findings of this report lay the groundwork for the next phase of the TransH2 project, contributing to the hydrogen system design.

5 Introduction

The maritime industry is currently undergoing a transformation driven by stringent emissions regulations, technological advancements, and increasing environmental concerns. The International Maritime Organization (IMO) has set ambitious targets for greenhouse gas reduction, calling for zero- emissions from international shipping by 2050 and aiming for full decarbonization within the century. As a response, hydrogen has emerged as one of the most promising alternatives to conventional marine fuels due to its high energy density, zero-emission potential and compatibility with fuel cell technology. Unlike fossil fuels, hydrogen combustion or fuel cell conversion does not produce carbon dioxide, particulate matter, or sulfur oxides, making it an ideal candidate for sustainable maritime applications. However, the successful implementation of hydrogen-powered vessels requires addressing several critical challenges, including fuel storage, energy conversion efficiency, safety considerations and infrastructure development. This report serves as a comprehensive analysis of the optimal configuration for hydrogen-powered passenger vessels, with a particular focus on identifying the most efficient propulsion architectures and energy system layouts. The findings presented herein build upon previous research and technical assessments conducted within the TransH2 project, incorporating peer-reviewed studies and insights from real-world applications of hydrogen propulsion in maritime environments.

Special attention is given to the selection of the energy conversion systems, hydrogen storage solutions, and hybrid powertrain architectures that can optimize vessel performance while ensuring operational reliability and cost-effectiveness.

Additionally, the report examines regulatory and safety considerations, given that hydrogen, while offering significant environmental benefits, presents unique handling and operational risks that must be mitigated through robust design and engineering solutions.

As part of the TransH2 project's broader objectives, this report does not merely provide a theoretical overview of hydrogen-based ship propulsion but also serves as a foundation for real-world implementation. The conclusions drawn from this study will directly contribute to the next phases of the project, particularly the development of prototype vessels and the establishment of fueling infrastructure at key maritime hubs in the Adriatic region. By synthesizing data from multiple sources, including previous Interreg maritime transport studies, international best practices, and experimental pilot projects, this document aims to provide a clear roadmap for ship designers, policymakers, and industry stakeholders who are working toward a greener maritime future.

Ultimately, this report will serve as a strategic guide for making informed decisions on optimal ship configurations, helping to pave the way for an efficient, safe, and economically viable hydrogen-powered maritime transport network. The following sections will delve into the methodologies used in this study, the state of the art in hydrogen propulsion, the technical and environmental considerations shaping optimal configurations, and the recommendations for future implementation.

6 Methodology

The approach taken in this report to determine the optimal configuration for hydrogen fueled passenger ships is based on a comprehensive analysis that integrates technical assessments, literature reviews, real-world case studies, and peer-reviewed research. The objective is to synthesize existing knowledge while applying a systematic methodology that evaluates multiple configurations of hydrogen-based propulsion and energy storage systems. This methodological framework ensures that the recommendations provided in this report are grounded in both theoretical research and practical feasibility, leading to solutions that can be effectively implemented in maritime operations.

The first step in this methodology involves an extensive literature review of hydrogen propulsion technologies, including energy conversion systems (FC, ICE) and hybrid solutions that combine batteries with hydrogen power. By analysing existing research, technical papers, and regulatory guidelines, this report identifies the strengths and limitations of different hydrogen propulsion architectures and assesses their applicability to passenger vessels operating in the Adriatic region. The literature review also includes an examination of ongoing pilot projects and operational hydrogen-fueled vessels, such as Norway's MF Hydra, the United States' MV Sea Change, and the Energy Observer, a research vessel powered by renewable energy and onboard hydrogen production. These case studies provide valuable insights into the real-world performance, operational challenges, and technological advancements that inform the optimal configuration selection.

This methodology is based on the technical assessment, economic viability and safety assessment of machinery setups and propulsion architectures. The evaluation at its first phase considers parameters as storage energy density, efficiency, technology readiness, safety aspects, etc., then after the identification of the optimal configuration, as a second step, the solution will be applied to the two reference vessels identified on the basis of the analysis performed in A2.1.

Output from the A2.2 and A2.1 will be used in the A2.3 to define the on-shore storage and refuelling infrastructure requirements.

By a multi-criteria analysis, the activity aims to determine the most effective combination of propulsion technology and energy storage that meets the operational needs of passenger vessels services while ensuring sustainability and cost-effectiveness.

The multicriteria decision analysis (MCDA) was used to systematically evaluate different configurations based on their economic, environmental, and technical viability. This approach enables a structured comparison of multiple hydrogen-powered vessel configurations, considering factors such as emissions reduction, lifecycle costs, infrastructure compatibility, safety implications, and regulatory compliance. The MCDA framework helps to identify trade-offs between different solutions and supports decision-making processes by prioritizing configurations that offer the highest overall performance while minimizing operational risks.

To ensure practical applicability, the methodology includes consultations with industry stakeholders, shipbuilders, maritime engineers, and regulatory bodies. This collaborative approach allows the report to reflect industry perspectives and real-world constraints, making the recommendations more relevant to ferry operators, port authorities, and policymakers. Furthermore, the methodology aligns with the broader objectives of the TransH2 project, integrating data from previous deliverables on maritime passenger routes, environmental impact assessments, and hydrogen-fueled vessel options to provide a cohesive and well-rounded analysis. By employing this comprehensive methodology, the report systematically evaluates hydrogen propulsion technologies, identifies optimal configurations, and provides actionable recommendations for the future development of hydrogen-powered passenger ferries.

7 Literature Review

The advancement of hydrogen-fueled passenger ships necessitates a comprehensive understanding of current research, technological developments, and practical applications of hydrogen propulsion systems. This literature review consolidates information from academic publications, technical reports, industry analyses, and case studies to provide a thorough foundation for assessing the optimal configuration of hydrogen-powered vessels. By examining state-of-the-art technologies, operational experiences, and regulatory frameworks, this section offers detailed insights into the present state of hydrogen-based maritime propulsion and its potential for widespread adoption.

In recent years, hydrogen propulsion in maritime transport has garnered significant attention due to increasing regulatory pressures to reduce greenhouse gas emissions. The International Maritime Organization (IMO) has established ambitious targets for emission reductions, positioning hydrogen as a key candidate for achieving these objectives. Unlike traditional fossil fuels, hydrogen combustion or electrochemical conversion in fuel cells produces zero carbon dioxide emissions, making it a viable solution for sustainable shipping. However, the broad adoption of hydrogen propulsion faces several technical and economic challenges, including energy efficiency, fuel storage, safety concerns, and infrastructure requirements.

Research on hydrogen propulsion for maritime applications primarily focuses on two main technologies: hydrogen fuel cells and hydrogen internal combustion engines (H2-ICE). Fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), are widely regarded as the most promising technology for passenger vessels due to their high efficiency, zero emission characteristics and scalability. Studies have shown that PEMFCs achieve energy conversion efficiencies of 50-60%, significantly higher than conventional diesel engines. Additionally, Solid Oxide Fuel Cells (SOFCs) have been investigated for maritime applications due to their ability to operate on multiple fuels, including ammonia and hydrogen, and their potential for higher efficiency, albeit with longer startup times.

Hydrogen storage methods are another critical topic in the literature, as the choice of storage technology directly impacts vessel design, operational efficiency, and safety. Three primary storage methods have been explored: compressed hydrogen gas (CH2), liquid hydrogen (LH2), and liquid organic hydrogen carriers (LOHC). Compressed hydrogen is the most commonly used storage method due to its simplicity and widespread availability, but it requires pressure tanks (typically 350-700 bar) that increase vessel weight and space requirements.

Liquid hydrogen storage offers higher energy density and lower storage volume but necessitates cryogenic temperatures of -253°C, introducing additional complexity in handling and insulation. Liquid Organic Hydrogen Carriers (LOHCs) are chemical compounds that can absorb and release hydrogen through reversible chemical reactions. They enable safe, dense and non-pressurized storage and transport of hydrogen in liquid form under ambient conditions. Unlike compressed or liquefied hydrogen, LOHCs are non-explosive and stable, making them well-suited for long-distance transport and integration into existing fuel infrastructure. To retrieve the hydrogen, the LOHC is heated in a dehydrogenation unit, after which the carrier can be reused.

The review of operational case studies provides valuable insights into the practical challenges and successes of hydrogen-powered vessels. Norway's MF Hydra, the world's first liquid hydrogen-powered ferry, has demonstrated the feasibility of LH2 storage and PEM fuel cell propulsion in commercial maritime operations. Similarly, the MV Sea Change in the United States utilizes compressed hydrogen with fuel cells, highlighting the potential for hydrogen ferries in urban water transport. The Energy Observer, a research vessel powered by a combination of solar, wind, and onboard hydrogen generation, showcases the integration of hydrogen with renewable energy sources, an area of increasing interest in the maritime sector.

A recurring theme in the literature is the need for supporting infrastructure, particularly hydrogen refueling stations at ports. Several studies emphasize that the economic viability of hydrogen-fueled passenger ferries depends not only on technological advancements but also on the development of a robust hydrogen supply chain. Ports must invest in hydrogen production, storage, and refueling facilities to support the adoption of hydrogen vessels. European projects such as H2Ports and the Clean Hydrogen Alliance are actively working on these challenges, paving the way for broader implementation of hydrogen-based maritime transport.

Safety considerations are another crucial aspect covered in the literature, given hydrogen's flammability and the need for strict handling protocols. Research highlights the importance of leak detection systems, explosion-proof ventilation, and emergency shutdown mechanisms in hydrogen vessel design. Regulatory bodies, including the IMO and classification societies like Lloyd's Register and DNV, are actively developing guidelines for hydrogen-powered ships to ensure compliance with safety standards.

The economic feasibility of hydrogen propulsion has been a significant focus of research, with studies comparing the total cost of ownership (TCO) of hydrogen-fueled vessels to conventional diesel and LNG-powered ships. While hydrogen currently remains more expensive due to production and distribution costs, projections indicate that increasing investment in green hydrogen production and fuel cell technology will lead to cost reductions over the next decade. The literature suggests that government incentives, carbon pricing mechanisms, and technological advancements will play a crucial role in making hydrogen a competitive alternative in maritime transport.

This literature review establishes a strong foundation for the subsequent analysis of optimal hydrogen-fueled passenger ship configurations. By integrating insights from past research, real-world applications and industry trends, this report aims to provide a comprehensive evaluation of the most effective technological solutions for sustainable maritime transport. The following sections will delve into the technical assessments, propulsion architectures, and energy system layouts necessary to achieve the optimal configuration for hydrogen-powered passenger ferries.

8 Energy layout system options

The design of an efficient and safe energy system layout is a fundamental aspect of integrating hydrogen propulsion on board. The energy system consists of several interrelated components, including hydrogen storage, fuel distribution, power conversion, and thermal management. The optimal configuration of these elements directly impacts vessel efficiency, operational range, safety, and compliance with maritime regulations. Given the challenges associated with hydrogen as a marine fuel, including its low volumetric energy density, flammability, and cryogenic storage requirements, careful planning of the energy system layout is necessary to ensure seamless operations and reliability.

8.1 Hydrogen Storage

The selection of an appropriate hydrogen storage method is one of the most critical factors in the energy system design. Storage technologies must balance energy density, safety, system weight, integration complexity, and regulatory compliance. Broadly, hydrogen storage methods can be categorized into physical-based and material-based technologies. Each has specific characteristics that influence its suitability for maritime use.

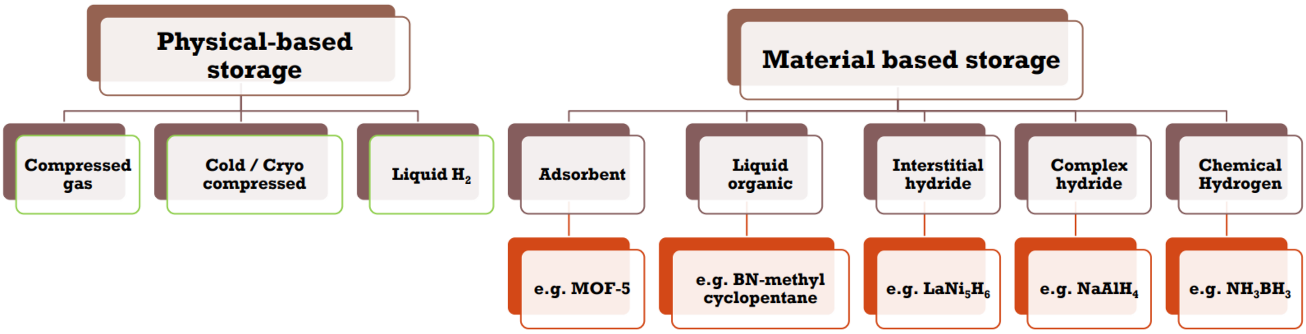

Figure 8-1Hydrogen storage options

Compressed hydrogen storage involves storing hydrogen gas in high-pressure vessels, typically at 350 bar (used for larger vessels or buses) or 700 bar (used in automotive and limited vessel applications). These tanks are made of advanced composite materials (Type III or IV) to withstand the high internal pressures while minimizing weight.

- Advantages:
  - Commercially mature and widely available
  - Fast refuelling capability
  - Relatively simple integration into existing ship architectures
- Challenges:

- Low volumetric energy density (≈ 23 kg/m³ at 350 bar)
- Requires large tank volume for long-range operations
- Safety considerations related to high-pressure containment

Figure 8-2 Compressed hydrogen tanks

Compressed hydrogen is particularly suited for short to medium-range passenger vessels and ferries where frequent refuelling is feasible. Compressed hydrogen (CH2) at 350-700 bar is the most widely used storage method due to its maturity and relatively straightforward implementation. However, high-pressure storage requires reinforced tanks, which increase vessel weight and occupy significant onboard space (Zhou et al., 2021).

Liquid hydrogen is stored cryogenically at −253 °C in vacuum-insulated double-wall tanks. This method offers higher volumetric energy density compared to compressed hydrogen, making it attractive for longer-range or high-power vessels.

- Advantages:
  - High volumetric density (~70.8 kg/m³)
  - Lower storage pressure (1–10 bar)
  - Suitable for large vessels with high hydrogen demand (e.g. cruise ships, RoPax)
- Challenges:
  - Significant energy input for liquefaction (~30% of H_2 energy content)
  - Boil-off losses during storage and operation, requiring either reliquefaction or controlled venting of excess hydrogen.
  - Complex cryogenic tank systems and safety management
  - Limited commercial availability in the marine sector

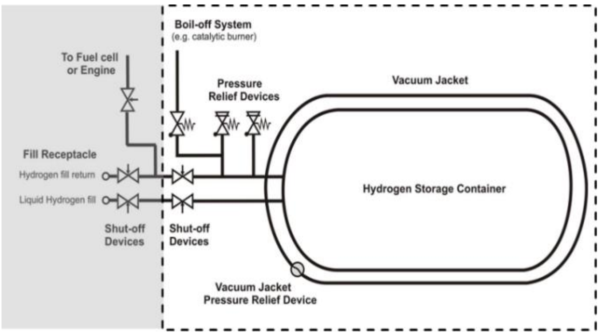

Figure 8-3 Liquid hydrogen storage

While LH2 presents challenges in terms of infrastructure development, it is increasingly being adopted in maritime projects, as demonstrated by the MF Hydra ferry in Norway, the world's first operational liquid hydrogen-powered vessel and as studied in the on going EU project sHYpS.

Figure 8-4 Liquid hydrogen tanks based on swappable concept developed in sHYpS EU co-funded project

LOHCs are liquid compounds (e.g. dibenzyltoluene) that chemically bind hydrogen and release it via a catalytic dehydrogenation process at high temperatures (250–320 °C). The liquid form allows use of conventional fuel infrastructure and tanks.

- Advantages:
    - Ambient temperature and pressure storage
    - High safety (non-toxic, non-flammable in hydrogenated state)
    - Compatible with existing liquid fuel logistics
- Challenges:
    - High thermal energy required for dehydrogenation
    - Lower round-trip efficiency compared to physical methods
    - Carrier regeneration may need land-based infrastructure

LOHCs are especially promising for bulk transport of hydrogen to ports, onboard hotel load systems, or hybrid configurations, where their safe handling and energy buffering features are valuable.

As already mentioned, the evaluation to find out the optimal energy system configuration starts considering these three possible hydrogen storage technologies. These will be then combined with the three options for energy conversion.

In the images below, the criteria related to the hydrogen storage that have been considered in the multi-criteria analysis are reported. The bar graphs are made considering the assigned values for each criterion.

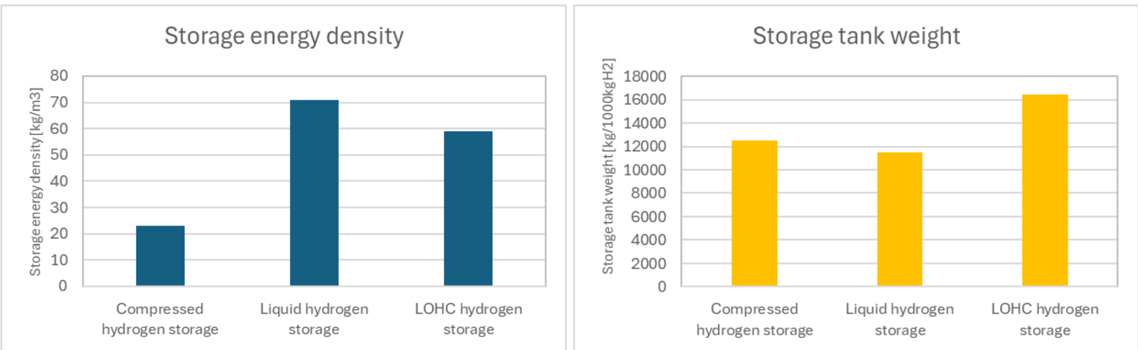

Figure 8-5 Assigned values for Storage energy density and Storage tank weight criteria

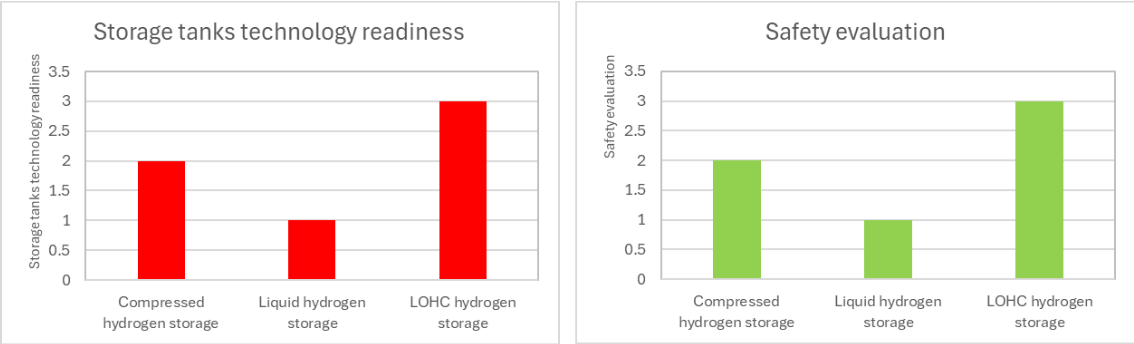

Figure 8-6 Assigned values for Storage tank readiness and safety evaluation criteria

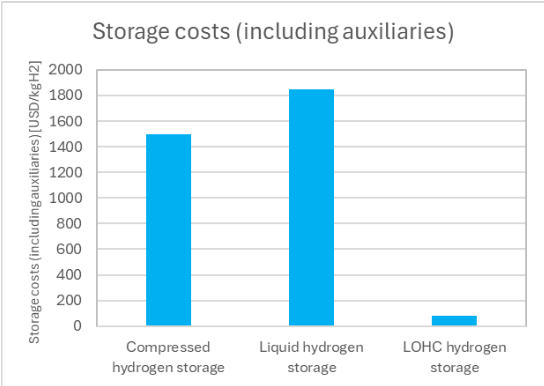

Figure 8-7 Assigned values for Storage costs criterion

8.2 Fuel Distribution System

The distribution of hydrogen from storage tanks to fuel cells or internal combustion engines requires a highly secure and efficient delivery system. Hydrogen must be supplied at the correct pressure and flow rate, with minimal energy losses during transportation. A typical fuel supply system includes high-pressure regulators, insulated transfer lines, flow control valves and leak detection sensors.

For compressed hydrogen, a cascade delivery system is often used to maintain pressure balance and prevent excessive gas expansion. Liquid hydrogen systems, on the other hand, require cryogenic transfer lines and vaporization units to convert liquid hydrogen into gaseous form before it enters the fuel cell. Given hydrogen's low molecular weight and tendency to diffuse through materials, specialized sealing technologies and reinforced piping systems are necessary to prevent leaks and ensure operational safety (Shu et al., 2022).

One of the most important aspects of hydrogen distribution is redundancy planning and safety integration. Hydrogen supply lines must be equipped with emergency shut-off valves and venting systems to allow rapid isolation in case of leaks or system failures. Explosion proof compartments and dedicated ventilation channels help prevent hydrogen accumulation in enclosed areas, reducing the risk of fire hazards (Lloyd's Register, 2023).

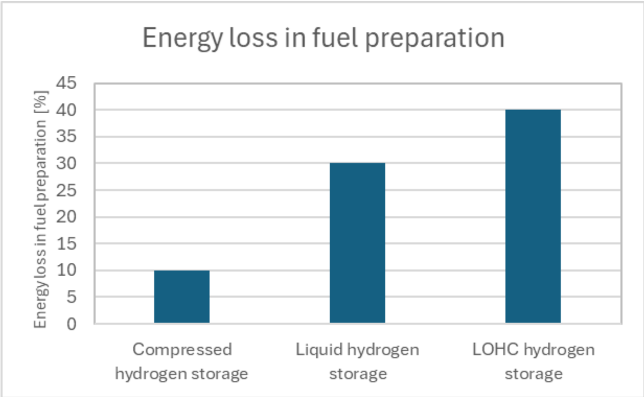

Figure 8-8 Assigned values for Energy loss in fuel preparation criterion

Additionally, integrating real-time gas monitoring sensors ensures immediate detection of any leaks, enabling automatic safety responses.

This part has been considered in the evaluation by the estimation of the energy loss for the fuel preparation.

8.3 Energy conversion

In marine applications, energy conversion systems play a crucial role in transforming hydrogen fuel into usable power for propulsion and onboard services. These systems primarily include fuel cells, such as Proton Exchange Membrane Fuel Cells (PEMFCs) and Solid Oxide Fuel Cells (SOFCs), as well as hydrogen internal combustion engines (H_2 ICEs). Each technology offers distinct advantages in terms of efficiency, emission profiles, integration complexity, and operational dynamics. The choice between these technologies depends on multiple factors, including efficiency, emissions, scalability and compatibility with existing maritime systems.

Hydrogen-powered vessels primarily rely on two propulsion technologies: hydrogen fuel cells and hydrogen internal combustion engines (H2-ICE).

Proton Exchange Membrane Fuel Cells (PEMFCs) are currently the most widely adopted hydrogen power source in maritime applications due to their high efficiency and rapid response time. PEMFCs operate by converting hydrogen and oxygen into electricity through an electrochemical reaction, with water as the only by-product (Ballard Power Systems, 2023). They offer energy conversion efficiencies between 50% and 60%, significantly outperforming conventional diesel engines, which typically achieve efficiencies of only 30-40% (Wang et al., 2022). Additionally, PEMFCs provide smooth and quiet operation, reducing noise pollution. A crucial advantage for passenger ferries operating in urban and environmentally sensitive areas.

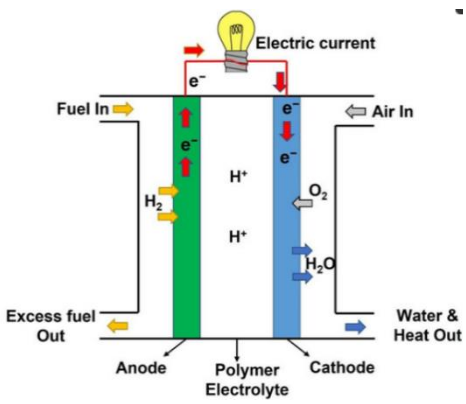

Figure 8-9 Basic schematic diagram of the PEMFC

Solid Oxide Fuel Cells (SOFCs) have also been considered for maritime applications due to their superior efficiency, reaching up to 65% (Shu et al., 2022). Unlike PEMFCs, which require high-purity hydrogen, SOFCs can utilize multiple fuels, including ammonia and methane, making them more adaptable in cases where hydrogen supply infrastructure is still under development. However, SOFCs operate at very high temperatures (typically above 700°C), requiring extensive thermal management systems and longer startup times, which limits their suitability for passenger ferries that require frequent stop-and-go operation.

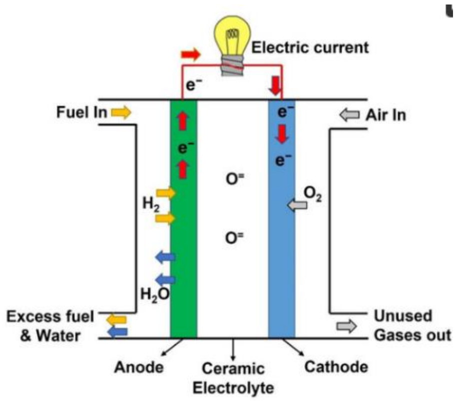

Figure 8-10 Basic schematic diagram of the SOFC

The integration of fuel cells with an energy management system (EMS) is critical for optimizing performance and fuel consumption. Advanced EMS solutions dynamically regulate power output based on real-time demand, ensuring that hydrogen is consumed efficiently while maintaining operational flexibility (Kumar et al., 2023). Fuel cells are typically coupled with lithium-ion battery systems, which help buffer energy fluctuations and improve load management. These hybrid fuel cell-battery setups allow the fuel cells to operate at their optimal power output, extending their lifespan and reducing overall hydrogen consumption. In peak power demand scenarios, such as vessel acceleration or docking maneuvers, the battery provides supplementary power, reducing strain on the fuel cell system.

Hydrogen Internal Combustion Engines (H2-ICEs) present an alternative to fuel cells, particularly for retrofitting existing vessels. Unlike traditional marine engines, which burn fossil fuels, H2-ICEs operate by combusting hydrogen in modified diesel-cycle or spark ignition engines. The primary advantage of H2-ICEs is their compatibility with existing maritime propulsion systems, allowing for easier integration with conventional gearboxes and drivetrains. However, H2-ICEs are less efficient than fuel cells, with an energy conversion efficiency of approximately 40%, and they produce small amounts of nitrogen oxides (NOx) due to high combustion temperatures (Verhelst et al., 2021). While Nox emissions can be mitigated through exhaust after-treatment systems, this additional complexity makes H2-ICEs less attractive for new vessel designs compared to fuel cell propulsion. The H2-ICE technology for marine application is still under development.

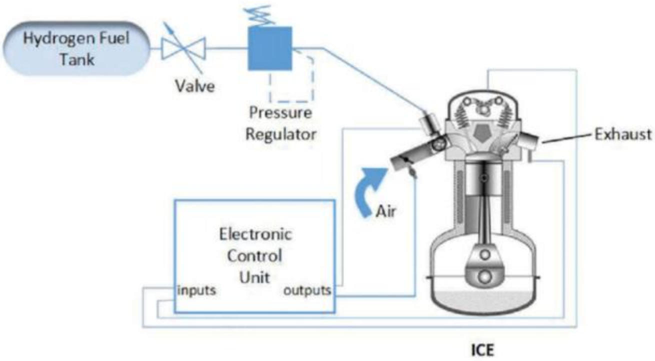

Figure 8-11 Basic schematic of H2-ICE main components

Thermal management is another key consideration in machinery setup. Both PEMFCs and SOFCs generate waste heat during operation, which must be effectively dissipated to maintain system efficiency and prevent overheating. PEMFC systems often incorporate liquid cooling circuits, while SOFCs require high-temperature heat exchangers and exhaust gas recirculation systems (Zhou et al., 2021). The captured waste heat from SOFCs can be repurposed for auxiliary onboard functions, such as heating and desalination, further improving overall system efficiency.

Figure 8-12 Pressure-boosted H2ICE

Maintenance and durability also influence the choice of machinery setup. PEMFCs require regular inspection of membrane electrode assemblies (MEAs), as degradation over time can reduce performance. The expected operational lifespan of a PEMFC in maritime applications is between 20,000 and 30,000 hours, after which stack replacement may be necessary (Ballard Power Systems, 2023). In contrast, SOFCs have longer lifespans but require specialized maintenance due to their high operating temperatures and complex ceramic electrolyte structures. H2-ICE systems, while mechanically simpler, require modifications to fuel injection and combustion chamber materials to handle the unique properties of hydrogen, including its high flame speed and low energy density per unit volume.

The three above listed options have been considered in the multi-criteria analysis in combination with the already described three storage options. For their evaluation the following characteristics have been considered:

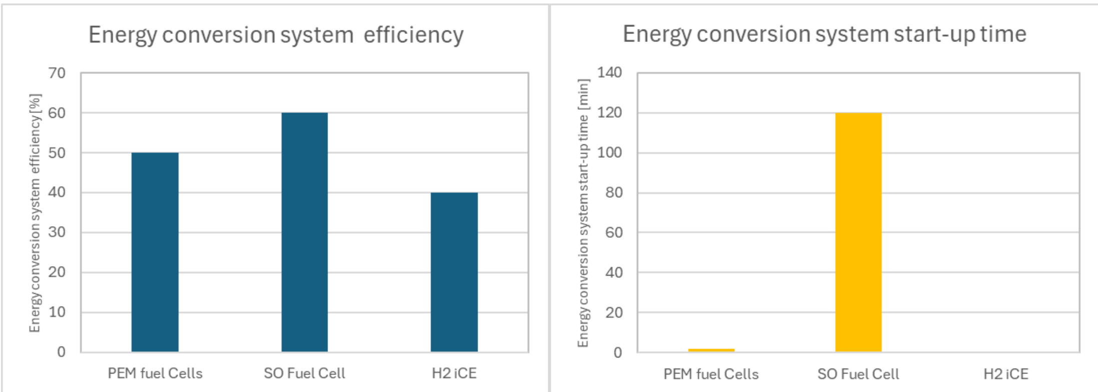

Figure 8-13 Assigned values for the Energy conversion system efficiency and Energy conversion system start-up time criteria

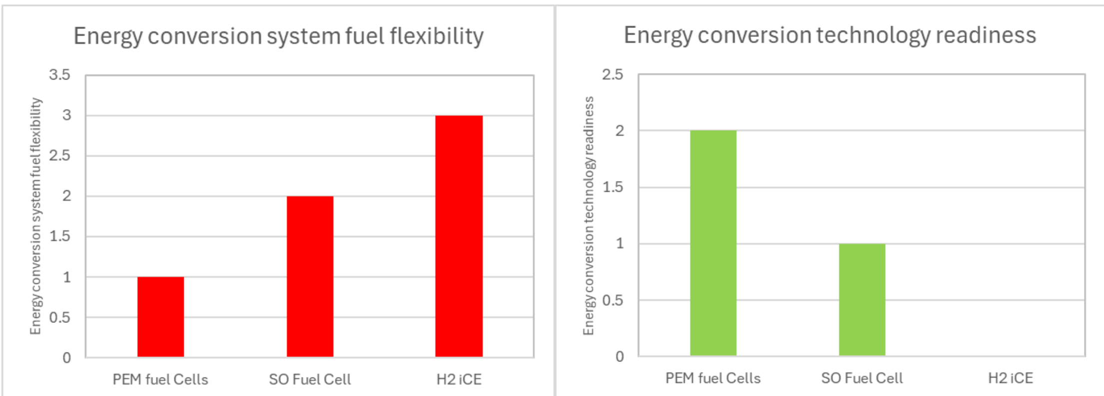

Figure 8-14 Assigned values for the Energy conversion system fuel flexibility and Energy conversion technology readiness criteria

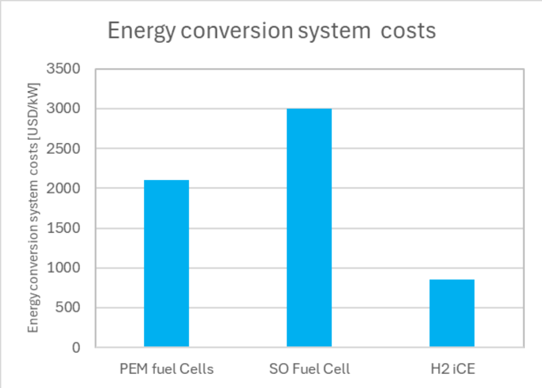

Figure 8-15 Assigned values for the Energy conversion system costs

8.4 Other aspects of the hydrogen system

The following information is provided for completeness and outlines additional aspects of the onboard hydrogen system. These elements were not included in the scope of the multicriteria analysis.

Power Conversion and Energy Management

The integration of fuel cells or hydrogen internal combustion engines, batteries and power management systems plays a crucial role in determining the overall efficiency and reliability of the hydrogen-powered vessels. The power conversion system transforms the electricity generated by fuel cells into usable power for propulsion and onboard systems. Fuel cells produce DC (direct current) electricity, which must be converted into AC (alternating current) for electric propulsion motors. A typical power conversion system includes:

- DC/DC converters to regulate fuel cell output voltage.
- DC/AC inverters for electric motor drive systems.
- Battery integration modules for hybrid energy storage.

Hybrid configurations that combine fuel cells with lithium-ion batteries allow for dynamic load balancing, ensuring that fuel cells operate at optimal efficiency while providing energy reserves for peak demand (Kumar et al., 2023). Batteries also allow regenerative energy recovery, storing excess energy generated during braking and deceleration for later use. Energy management systems (EMS) coordinate the interaction between fuel cells, batteries, and onboard electrical loads, optimizing fuel consumption and preventing overloading of any single component.

Thermal Management and Waste Heat Recovery

Both PEM fuel cells and hydrogen internal combustion engines generate excess heat that must be dissipated to maintain system stability. Effective thermal management is critical for preventing overheating and improving overall system efficiency.

- Fuel cell cooling systems typically use liquid coolant loops to regulate stack temperature and prevent thermal degradation.
- Cryogenic hydrogen storage systems require active insulation layers and vacuum jacketed piping to minimize heat ingress.
- Waste heat recovery units can capture and repurpose excess thermal energy for onboard heating, desalination, or auxiliary power generation (Zhou et al., 2021).

Solid Oxide Fuel Cells (SOFCs), which operate at temperatures above 700°C, provide opportunities for high-efficiency waste heat utilization, making them attractive for hybrid systems where residual heat can be used for secondary power applications. However, their slow startup time limits their applicability in passenger ferries requiring rapid deployment.

Safety and Regulatory Considerations

Ensuring compliance with IMO, SOLAS and classification society standards is a fundamental requirement for the implementation of hydrogen-based energy systems. The IGF Code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels) provides guidelines for hydrogen handling, storage and system integration (Lloyd's Register, 2023). Key safety measures include:

- Dedicated hydrogen storage compartments with fireproof barriers.
- Automated hydrogen leak detection and emergency shutdown systems.
- Controlled venting systems to prevent gas accumulation.
- Explosion-proof electrical components.

Additionally, classification societies such as Lloyd's Register and DNV have developed specific guidelines for hydrogen-powered ships, outlining best practices for tank placement, fire suppression, and explosion-proof enclosures (Lloyd's Register, 2023). Compliance with these regulations is essential for ensuring the safe operation of hydrogen vessels in commercial service.

To further enhance safety, crew training programs and emergency response protocols must be implemented to ensure operators are equipped to handle hydrogen-related incidents effectively.

Propulsion architectures

Hydrogen-fueled vessels can adopt either a fully electric propulsion system, where fuel cells generate electricity for electric motors, or a hybrid system that combines fuel cells with batteries to optimize power delivery. Fully electric propulsion offers simplicity and reliability, with fewer mechanical components and reduced maintenance requirements compared to internal combustion-based systems (Kumar et al., 2023). However, integrating battery storage with fuel cells enhances system efficiency by allowing load balancing and peak shaving, reducing hydrogen consumption and extending fuel cell lifespan. Hybrid architectures also enable regenerative energy recovery, particularly useful for ferries operating in regions with frequent stop-and-go operations, such as urban waterways.

Battery-assisted propulsion also enables regenerative braking in certain vessel designs, capturing excess energy during deceleration and feeding it back into the system. This feature is particularly useful for ferries operating on short, frequent routes where docking and undocking cycles occur multiple times per hour. Additionally, batteries provide a redundant energy source, ensuring that the vessel can operate temporarily on stored energy if there is an issue with the hydrogen supply or fuel cell system.

One challenge of hybrid architectures is the added weight and volume of battery storage. Unlike fuel cells, which continuously generate power as long as hydrogen is available, batteries require additional space for installation, increasing the vessel's displacement. However, advancements in solid-state battery technology and high-density energy storage solutions are addressing these limitations, making hybrid fuel cell-battery configurations increasingly viable for passenger ferries (Zhou et al., 2021).

Hydrogen refuelling infrastructure

The integration of hydrogen refueling infrastructure is another essential factor in determining the feasibility of hydrogen-fueled ships. Ports must be equipped with hydrogen storage, compression, and dispensing systems capable of refueling vessels efficiently while adhering to safety regulations. Studies have shown that a lack of refueling infrastructure remains one of the primary barriers to hydrogen adoption in the maritime sector (Verma et al., 2023). In response, initiatives such as the European H2Ports project and the Clean Hydrogen Alliance are working to develop port-based hydrogen supply chains that can support the widespread deployment of hydrogen-powered vessels.

The optimal energy system layout for hydrogen-powered passenger ferries depends on multiple factors, including storage method, power conversion strategy and thermal management.

The next section will explore multicriteria analysis technique used to evaluate different configurations, comparing economic, environmental and technical performance factors to determine the most viable hydrogen-powered passenger ferry solutions.

9 Multicriteria Analysis

The selection of an optimal hydrogen-fueled propulsion configuration for passenger vessels requires a systematic and quantitative evaluation of multiple factors, balancing technical feasibility, economic viability, environmental impact and regulatory compliance. Given the complexity of hydrogen propulsion systems, a Multicriteria Decision Analysis (MCDA) approach is employed to assess different configurations against key performance indicators. This methodology allows decision-makers to compare trade-offs between various hydrogen-based technologies and select the most suitable option based on operational, economic and environmental priorities.

Methodological Approach

Multicriteria Decision Analysis (MCDA) is a structured framework used to evaluate complex systems where multiple objectives must be considered simultaneously. The MCDA process involves:

1. Defining evaluation criteria based on technical, economic, environmental and safety parameters.
2. Identifying candidate propulsion configurations, including different energy conversion systems (PEMFCs, SOFCs and H2ICE) and different hydrogen storage options (compressed hydrogen, liquid hydrogen, LOHC).
3. Assigning weight factors to each evaluation criterion based on stakeholder priorities and industry benchmarks.
4. Scoring each alternative according to how well it meets the defined criteria.
5. Applying decision-making models, such as Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), to rank and select the best configuration.

This structured evaluation ensures that the chosen hydrogen propulsion system aligns with both short-term feasibility and long-term sustainability goals in maritime transport.

Evaluation Criteria

To comprehensively assess different hydrogen propulsion configurations, the following three primary evaluation categories are considered:

1. Technical Performance

- Storage system energy density: Indication of how many kilograms of hydrogen can be stored in 1 m3.
- Storage tank weight: Added weight in kg to store 1000 kg of hydrogen
- Energy conversion system efficiency: Fuel-to-power conversion efficiency, including losses in fuel cells or combustion engines.
- Energy loss in fuel preparation: includes losses for heating and evaporation of liquid hydrogen, dehydrogenation for the LOHC, etc
- Energy conversion system start-up time: estimated time for the readiness of the system
- Energy conversion system fuel flexibility: ranking of the three conversion systems

- Energy conversion system readiness: estimation of the technology readiness to be used for an installation on board
- Storage tanks technology readiness: estimation of the technology readiness to be used for an installation on board

2. Economic Feasibility

- Storage system CAPEX cost (including auxiliaries) [USD/kWh]
- Energy conversion system CAPEX cost [USD/kWh]

3. Environmental Impact

- Air quality impact: Emission of nitrogen oxides (NO_x) from H2-ICE systems versus zero-emission fuel cells.

4. Regulatory and Safety Compliance

- Safety considerations: Risk of hydrogen leaks, explosion-proof storage requirements and emergency response protocols.
- Infrastructure readiness: Availability of port-side refueling and storage infrastructure.

<u>Comparison of Hydrogen Propulsion Configurations</u>

Using the defined evaluation criteria, nine primary hydrogen propulsion configurations are assessed:

1. PEM FCs with compressed hydrogen storage
    - Pros: High efficiency (50-60%), zero emissions, quiet operation, and modular scalability, low energy loss for fuel preparation.
    - Cons: High initial CAPEX, limited hydrogen refueling infrastructure, low energy storage density and sensitivity to hydrogen purity.
2. PEM FCs with liquid hydrogen storage
    - Pros: High efficiency (50-60%), zero emissions, quiet operation and modular scalability.
    - Cons: High initial CAPEX, limited hydrogen refueling infrastructure, and sensitivity to hydrogen purity, high energy loss for fuel preparation, boil-off gas management.
3. PEM FCs with LOHC hydrogen storage
    - Pros: High efficiency (50-60%), zero emissions, quiet operation, modular scalability, high storage technology readiness, very low storage cost, high safety
    - Cons: High initial CAPEX and sensitivity to hydrogen purity, very high energy loss for fuel preparation.
4. SOFCs with compressed hydrogen storage

- Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low energy loss for fuel preparation, low sensitivity on hydrogen purity
- Cons: High initial CAPEX, low energy storage density, limited hydrogen refueling infrastructure, long start-up time

5. SOFCs with liquid hydrogen storage
    - Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low sensitivity on hydrogen purity, high energy storage density
    - Cons: High initial CAPEX, limited hydrogen refueling infrastructure, long start-up time, high energy loss for fuel preparation, boil-off gas management
6. SOFCs with LOHC hydrogen storage
    - Pros: Very high efficiency (60%), zero emissions, quiet operation, modular scalability, low sensitivity on hydrogen purity, high storage technology readiness, very low storage cost, high safety
    - Cons: High initial CAPEX, long start-up time, very high energy loss for fuel preparation
7. H2-ICEs with compressed hydrogen storage
    - Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, faster refueling, low energy loss for fuel preparation, low sensitivity on hydrogen purity
    - Cons: Low efficiency (~40%), low energy storage density, limited hydrogen refueling infrastructure, NO_x emissions
8. H2-ICEs with liquid hydrogen storage
    - Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, low sensitivity on hydrogen purity, high energy storage density
    - Cons: Low efficiency (~40%), high energy loss for fuel preparation, boil-off gas management, limited hydrogen refueling infrastructure, NO_x emissions
9. H2-ICEs with LOHC hydrogen storage
    - Pros: Compatibility with existing propulsion systems, relatively lower CAPEX, low sensitivity on hydrogen purity, high storage technology readiness, very low storage cost, high safety
    - Cons: Low efficiency (~40%), very high energy loss for fuel preparation, NO_x emissions

9.1 Methodology of multi-criteria assessment

The objective of the assessment is to identify, among a set of m feasible technical solutions for hydrogen-fuelled vessels operating on a specific route, the most promising option from technical, environmental and economic standpoints. Each of these dimensions requires distinct performance criteria, which often conflict with one another. Therefore, it is necessary to analyze the candidate options through these three lenses, define appropriate performance indicators and use them to enable a comparative evaluation.

Multi-Criteria Decision Analysis (MCDA) provides a structured framework to support this process. MCDA allows decision-makers to evaluate and prioritize alternatives by considering multiple and often conflicting criteria simultaneously. This approach is especially valuable in complex decision-making contexts, such as the maritime energy transition, where balancing technical performance, environmental impact and cost-effectiveness is essential.

At the core of MCDA is the performance matrix (also known as the decision matrix), which organizes the available options (typically as rows) against the selected evaluation criteria (as columns). Each cell of the matrix contains the performance value x_{ij} of option (i) with respect to criterion (j), expressed in the original measurement scale of that criterion. This matrix forms the basis for applying various MCDA methods, which are then used to compare, assess and in many cases, rank the alternatives according to their multi-dimensional performance.

This activity aims to evaluate all the options and building a final ranking of them in order to determine the one that has the most effective overall performance. As for the Activity 2.1, it was decided to use a well- established method that has frequently been used in technical or engineering problems[1]: the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution[2]) method.

The TOPSIS method is a widely adopted Multi-Criteria Decision Analysis (MCDA) technique used to rank alternatives based on their relative closeness to an ideal solution. It is particularly well-suited for decision-making contexts involving multiple, and potentially conflicting, criteria. The core principle of TOPSIS is that the optimal alternative should have the shortest distance from the ideal solution and the farthest distance from the anti-ideal (or worst-case) solution.

The application of the TOPSIS method involves several key steps. First, a performance matrix is constructed, in which each element represents the performance of a given alternative with respect to a specific criterion. This step requires a clear definition of the alternatives (options) under evaluation and the criteria against which they are assessed.

[1] For a recent review, see: Pandey, V., Komal, & Dincer, H. (2023). A review on TOPSIS method and its extensions for different applications with recent development. Soft Computing, 27(23), 18011-18039.

[2] Hwang, C.-L., & Yoon, K. (1981). Multiple Attribute Decision Making: Methods and Applications: a State-of-the-art Survey (p. 259). Springer-Verlag.

Option	Description	Storage energy density [kg/m3] (2)	Added weight for storage of 1t of hydrogen [kg]	Energy conversion system efficiency [%] (5)	Energy loss in fuel preparation [%] (6)	Energy conversion system start-up time [min]	Energy conversion system fuel flexibility	Energy conversion technology readiness	Storage tanks technology readiness	Storage costs (including auxiliaries) [USD/kg H2] (3)	Energy conversion system costs [USD/kW] (1)	NO_X production [g/kWh] (4)	Safety
1	PEMFCs with compressed H2 (350 bar)	23	12500	50	10	2	1	2	2	1500	2100	0	2
2	PEMFCs with liquid H2	70.8	12000	50	30	2	1	2	1	1850	2100	0	1
3	PEMFCs with LOHC	59	17000	50	45	2	1	2	2	1200	2100	0	3
4	SOFCs with compressed H2 (350 bar)	23	12500	60	10	120	2	1	2	1500	3000	0	2
5	SOFCs with liquid H2	70.8	12000	60	30	120	2	1	1	1850	3000	0	1
6	SOFCs with LOHC	59	17000	60	45	120	2	1	2	1200	3000	0	3
7	H2-ICE with compressed H2 (350 bar)	23	12500	40	10	0.5	3	0	2	1500	850	0.12	2
8	H2-ICE with liquid H2	70.8	12000	40	30	0.5	3	0	1	1850	850	0.12	1
9	H2-ICE with LOHC	59	17000	40	45	0.5	3	0	2	1200	850	0.12	3

Figure 9-1 Performance matrix

DATA SOURCES:
(1) Fredrik G.Aarskog, Janis Danebergs, Trond Stromgren and Oystein Ulleberg, Energy and cost analysis of a hydrogen driven high speed passenger ferry, 21 April 2020 Sustainability whitepaper, HYDROGEN AS MARINE FUEL, June 2021
(2) ABS, Sustainability whitepaper, Hydrogen as Marine Fuel, June 2021
(3) Fredrik G.Aarskog, Janis Danebergs, Trond Stromgren and Oystein Ulleberg, Energy and cost analysis of a hydrogen driven high speed passenger ferry, 21 April 2020 Sustainability whitepaper, HYDROGEN AS MARINE FUEL, June 2021 EU co-funded Shyps project data, 2025 BNEF Hydrogen Economy Outlook Key Messages 30 March 2020. 2020. Available (estimation by JPMorgan)
(4) Energy Homeland security, The future of H2 internal combustion engines in California
(5) Energy Homeland security, The future of H2 internal combustion engines in California EU co-funded sHYpS Project, 2025
(6) Estimated from litherature
(7) Qian Cheng, Ruiqiang Zhang, Zhusheng Shi, Jianguo Lin, Review of common hydrogen storage tanks and current manufacturing methods for aluminium alloy tank liners

Since the performance values are often expressed in diverse units and scales, the next step is the normalization of the matrix. This process standardizes the data, ensuring that all criteria are converted into a dimensionless, comparable form, which is essential for subsequent distance calculations. This is typically done using vector normalization; if x_{ij} is the value of the performance of option (i) in criterium (j) before the normalisation, the normalised value r_{ij} is:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_i x_{ij}^2}}$$

The normalised performance matrix includes all the normalised values.

The third step in the TOPSIS method involves incorporating the relative importance of each criterion through the assignment of weights. This allows decision-makers to reflect the varying significance of the criteria in the context of the specific decision problem. Each criterion is assigned a weight, and the normalized performance matrix is then multiplied by these weights to produce the weighted normalized performance matrix, where each element is denoted as v_{ij}.

In the case of the TransH2 project, it was decided to apply equal weights to all criteria, reflecting a uniform level of importance. Under equal weighting, the transformation results in a scaled version of the normalized matrix, preserving the relative performance values. This ensures that the sum of the weighted values for any given alternative does not exceed 1, maintaining consistency and comparability across the dataset.

The fourth step involves identifying the ideal (best) and anti-ideal (worst) solutions. These reference points do not correspond to actual alternatives but are instead hypothetical constructs derived from the performance of the available options. Each alternative is represented by a vector of weighted normalized performance values [v_{ij},j=1,…,n], where n is the number of criteria.

To define the ideal solution, the best performance values are selected across all criteria: maximum values for benefit criteria (where higher values are preferred) and minimum values for cost criteria (where lower values are preferred). Conversely, the anti-ideal solution consists of the minimum values for benefit criteria and maximum values for cost criteria. These two constructed vectors represent the benchmark extremes against which all actual alternatives are evaluated in subsequent steps of the TOPSIS method.

Option	Description	Storage energy density [kg/m3]	Added weight for storage of 1t of hydrogen [kg]	Energy conversion system efficiency [%]	Fuel preparation efficiency	Energy conversion system start-up time	Energy conversion fuel flexibility	Energy conversion technology readiness	Storage tanks technology readiness	Storage costs [USD/kg H2]	Energy conversion system costs	NO_x production	Safety
1	PEMFCs with compressed H2 (350 bar)	0.047	0.099	0.110	0.035	0.003	0.051	0.172	0.128	0.108	0.108	0.000	0.103
2	PEMFCs with liquid H2	0.143	0.095	0.110	0.105	0.003	0.051	0.172	0.064	0.133	0.108	0.000	0.051
3	PEMFCs with LOHC	0.120	0.135	0.110	0.157	0.003	0.051	0.172	0.128	0.087	0.108	0.000	0.154
4	SOFCs with compressed H2 (350 bar)	0.047	0.099	0.132	0.035	0.192	0.103	0.086	0.128	0.108	0.154	0.000	0.103
5	SOFCs with liquid H2	0.143	0.095	0.132	0.105	0.192	0.103	0.086	0.064	0.133	0.154	0.000	0.051
6	SOFCs with LOHC	0.120	0.135	0.132	0.157	0.192	0.103	0.086	0.128	0.087	0.154	0.000	0.154
7	H2-ICE with compressed H2 (350 bar)	0.047	0.099	0.088	0.035	0.001	0.154	0.000	0.128	0.108	0.044	0.192	0.103
8	H2-ICE with liquid H2	0.143	0.095	0.088	0.105	0.001	0.154	0.000	0.064	0.133	0.044	0.192	0.051
9	H2-ICE with LOHC	0.120	0.135	0.088	0.157	0.001	0.154	0.000	0.128	0.087	0.044	0.192	0.154
vj*	Best combination	0.143	0.095	0.132	0.035	0.003	0.103	0.172	0.128	0.087	0.044	0.000	0.154
vj*	Worst combination	0.047	0.135	0.088	0.157	0.192	0.051	0.000	0.128	0.133	0.154	0.192	0.051

Figure 9-2Weighted performance matrix

The fifth step is the calculation of the Euclidean distance of each alternative from the ideal and anti-ideal solutions (separation measures). For instance, if [vj*] is the vector that represents the ideal solution, then the separation measure of option (i) from the ideal solution (Di*) is

$$D_i^* = \sqrt{\sum_j \left(v_{ij} - v_j^*\right)^2}$$

Similarly, the separation measure from the anti-ideal solution (D_i^-) is calculated for all options.

Each alternative i is subsequently characterized by two key metrics: its distance from the ideal solution and its distance from the anti-ideal solution. It is important to emphasize that relying solely on one of these separation measures is insufficient for effective ranking. An option that is closest to the ideal solution may not necessarily be the farthest from the anti-ideal, and vice versa. Therefore, the sixth step involves computing a relative closeness coefficient to the ideal solution, denoted as C_i^*, which integrates both separation measures to determine the overall desirability of each alternative.

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}$$

The coefficient C_i^*ranges between 0 and 1, where a value of 0 indicates that option i coincides with the anti-ideal solution and a value of 1 signifies that it matches the ideal solution. This coefficient serves as a basis for ranking the alternatives, with higher values representing options that are more closely aligned with the ideal, and lower values indicating those closer to the worst-case scenario.

9.2 Results of the multicriteria assessment

By applying the above procedure, the overall performance of the options are:

Option	Description	Di*	Di-	Ci*
1	PEMFCs with compressed H2 (350 bar)	0.140	0.353	0.715
2	PEMFCs with liquid H2	0.170	0.351	0.673
3	PEMFCs with LOHC	0.156	0.374	0.705
4	SOFCs with compressed H2 (350 bar)	0.260	0.292	0.528
5	SOFCs with liquid H2	0.278	0.259	0.482
6	SOFCs with LOHC	0.269	0.289	0.518
7	H2-ICE with compressed H2 (350 bar)	0.289	0.309	0.516
8	H2-ICE with liquid H2	0.305	0.278	0.477
9	H2-ICE with LOHC	0.297	0.307	0.508

Figure 9-3 Measures of overall performance of the option

So the final ranking of the technical options are:

Ranking position	Option n°	Description	Coefficient of similarity
1	1	PEMFCs with compressed H2 (350 bar	0.715
2	3	PEMFCs with LOHC	0.705
3	2	PEMFCs with liquid H2	0.673
4	4	SOFCs with compressed H2 (350 bar)	0.528
5	6	SOFCs with LOHC	0.518
6	7	H2-ICE with compressed H2 (350 bar)	0.516
7	9	H2-ICE with LOHC	0.508
8	5	SOFCs with liquid H2	0.482
9	8	H2-ICE with liquid H2	0.477

Figure 9-4 Final ranking of the technical options

The ranking highlights the superior performance of PEM fuel cell (PEMFC) systems, which occupy the top three positions across all storage technologies considered. **The highest-ranked configuration is PEMFC with compressed hydrogen at 350 bar (Option 1),** achieving the greatest similarity to the ideal solution with a coefficient of 0.715. This reflects a strong balance across technical, economic and environmental criteria, likely due to its maturity, efficiency and compatibility with existing refueling infrastructure.

Closely following are PEMFCs with LOHC (Option 3) and with liquid hydrogen (Option 2), scoring 0.705 and 0.673, respectively. Their proximity to the top option confirms the robustness of PEMFC technology across different hydrogen storage strategies.

Solid Oxide Fuel Cells (SOFCs) rank in the mid-tier, with compressed hydrogen performing slightly better than LOHC and liquid H_2. SOFCs generally provide higher efficiency at steady state but may have been penalized in this evaluation due to lower technology readiness and slower dynamic response, both of which are critical for marine applications.

Hydrogen Internal Combustion Engines (H_2-ICE) consistently rank in the lower tier, with the lowest coefficient of 0.477 for H_2-ICE with liquid hydrogen. While H_2-ICE technology benefits from simplicity and mechanical familiarity, its lower efficiency, higher NO_x emissions, and mechanical complexity likely contributed to its weaker performance in this multicriteria context.

The best configuration that emerges from the multi-criteria analysis, which includes compressed hydrogen storage and a PEM fuel cell, will be implemented on both vessels operating along regional and international routes. As previously outlined in Activity 2.1, the key difference lies in the vessels' endurance when operating on hydrogen. The concept for regional routes envisions a fully hydrogen-powered vessel, whereas the design for international routes will adopt a hybrid solution, with hydrogen propulsion limited to port operations.

10 General recommendations for the hydrogen implementation on-board

10.1 Hydrogen Storage and Containment Safety

Given hydrogen's high flammability and low molecular weight, proper containment and ventilation are essential for preventing leaks and ensuring safe fuel storage. The main storage options, compressed hydrogen (CH2) and liquid hydrogen (LH2), present different safety challenges. To mitigate risks the following indications should be considered:

- Tanks must be placed in designated explosion-proof compartments, separate from passenger areas.
- Overpressure relief valves and automatic shutdown systems must be installed to prevent uncontrolled hydrogen release.
- Leak detection sensors and ventilation ducts should be incorporated to remove any leaked hydrogen before it accumulates in enclosed spaces.
- Liquid Hydrogen (LH2) Safety Measures: LH2 storage introduces additional safety considerations due to cryogenic temperatures (-253°C) and boil-off gas (BOG) management:
    - Tanks must be thermally insulated with multilayer vacuum insulation to prevent heat ingress and minimize evaporation losses.
    - Boil-off gas must be safely vented or re-liquefied to avoid pressure buildup in the storage tanks.
    - Cryogenic fuel transfer lines must be reinforced to prevent thermal stress fractures and leaks.

Both CH2 and LH2 storage solutions must adhere to IMO and classification society requirements, ensuring safe handling and operational reliability under maritime conditions.

10.2 Fire and Explosion Risk Mitigation

Hydrogen is highly flammable, requiring specialized fire protection systems to prevent thermal runaway, combustion, or explosion risks. The primary fire suppression strategies should include:

- Fire-Resistant Hydrogen Compartments: Fuel storage areas must be enclosed within fire-resistant compartments to prevent direct exposure to ignition sources. Materials used must comply with fire protection standards (IMO MSC.1/Circ.1558) to withstand extreme conditions.
- Inert Gas Purging Systems: To prevent hydrogen build-up, inert gases such as nitrogen can be used to purge fuel lines and storage tanks, reducing the risk of combustion.
- Explosion-Proof Electrical Components: All electrical circuits, sensors and control systems in hydrogen-prone areas must be explosion-proof to prevent accidental ignition.
- Automatic Leak Detection and Ventilation: Hydrogen sensors must be installed throughout the vessel to detect leaks in real time. Upon detection, automated ventilation systems should immediately activate to disperse hydrogen gas safely into the atmosphere (DNV, 2023).

- Hydrogen Flame Detectors: Unlike conventional fuels, hydrogen burns with an invisible flame, making infrared or ultraviolet flame detection systems essential for rapid fire response.

10.3 Crew Training and Emergency Response

Proper training for ferry operators and emergency responders is crucial for safely managing hydrogen-powered vessels. IMO regulations mandate that crews receive specialized training on handling alternative fuels, with specific focus on:

- Hydrogen Fuel Handling Procedures: Training on safe refueling, leak prevention and emergency shutdown protocols.
- Fire Suppression Drills: Crews must be trained to respond to hydrogen-related fire scenarios, including deployment of fire suppression agents and evacuation procedures.
- System Failure Simulations: Regular testing of fuel cell shutdown procedures, battery management systems and emergency power backups to ensure vessel operability during technical failures.

Hydrogen-powered vessels must also coordinate with port authorities, firefighters and coast guard units to ensure emergency response teams are equipped to handle hydrogen related incidents.

10.4 Regulatory Challenges and Future Outlook

Despite the existence of IMO, SOLAS and classification society guidelines, regulatory frameworks for hydrogen propulsion remain in the early stages of development. Several challenges must still be addressed to facilitate large-scale deployment:

- Lack of specific IMO rules for hydrogen ships: While the IGF Code provides general provisions for low-flashpoint fuels, additional amendments are needed to fully incorporate hydrogen-specific safety standards.
- Hydrogen refueling infrastructure gaps: Ports require specialized hydrogen refueling stations, but few global ports currently meet IMO safety standards for on-site hydrogen handling and bunkering (European Maritime Safety Agency, 2023).
- Standardization of hydrogen storage technologies: CH2 and LH2 storage solutions must be standardized across vessel types to streamline refueling operations and regulatory compliance.

To address these challenges, industry collaborations and research initiatives are actively working to refine hydrogen safety guidelines. The European H2Ports Project and the Clean Hydrogen Alliance are developing port safety protocols, while classification societies are updating technical standards for hydrogen vessel designs.

As regulatory frameworks continue to evolve, collaboration between governments, classification societies and maritime stakeholders will be critical in establishing a globally standardized hydrogen safety framework. The future of hydrogen-powered vessels will depend on the harmonization of safety regulations, port infrastructure expansion and continuous innovation in fuel storage and fire prevention technologies.

10.5 Vessel design

This section focuses on recommendations for optimizing hydrogen vessel designs, outlining best practices for implementing next-generation propulsion systems in passenger ferries.

Optimal Hydrogen Propulsion Configuration

The PEM FC and gaseous hydrogen storage emerges as the most viable configuration for hydrogen powered passenger ferries.

The combination with a battery systems (Lithium-ion battery storage) should be incorporated to buffer peak loads, improve fuel cell lifespan and enable regenerative braking during docking and deceleration.

Multi-stack fuel cell configurations should be adopted to ensure modular power generation, allowing for individual stack shutdowns without disrupting operations.

Advanced Energy Management Systems (EMS) should be implemented to optimize fuel cell-battery interaction and improve overall efficiency.

Hydrogen Storage and Refueling Strategy

Hydrogen bunkering facilities must be developed at major ferry ports, with a focus on on-site hydrogen production from renewable energy sources. Investments in port-side hydrogen compression, liquefaction and distribution pipelines will be essential for long-term adoption.

Vessel Design and Energy System Optimization

The integration of hydrogen fuel systems into ferry designs must consider space constraints, weight distribution and safety requirements.

- Hydrogen storage tanks should be positioned below deck or within dedicated fire-resistant compartments to improve vessel stability. Lightweight composite materials should be used to offset the additional weight of fuel cell stacks and storage systems.
- Waste heat recovery systems should be integrated for repurposing excess thermal energy for onboard use.
- Automated Leak Detection and Ventilation: To ensure operational safety, hydrogen powered ferries must include real-time gas monitoring sensors, automatic ventilation systems, and emergency shutdown mechanisms.

Regulatory Compliance and Safety Enhancements

Ensuring compliance with IMO, SOLAS, and classification society regulations is critical for the safe operation of hydrogen-powered ferries.

- Implementation of IMO IGF Code Requirements: Hydrogen storage and fuel handling must comply with explosion-proof enclosure standards, controlled venting systems, and fire suppression regulations.

- Crew Training and Safety Protocols: Ferry operators must undergo specialized training in hydrogen fuel handling, emergency response, and refueling procedures.

Regular safety drills should be conducted to simulate fire suppression and leak containment scenarios.

Scalability and Future-Proofing

To ensure long-term sustainability, hydrogen-powered ferries must be designed with future scalability in mind.

- Standardization of Hydrogen Systems: Common fuel cell sizes, hydrogen tank configurations, and refueling protocols should be adopted to streamline vessel manufacturing and refueling operations.
- Integration with Green Hydrogen Production: Ferry operators should invest in renewable hydrogen sourcing, leveraging wind, solar, and hydropower electrolysis to ensure 100% carbon-free operations.

Hydrogen-powered passenger ferries represent the next frontier in zero-emission maritime transport, offering a clean, efficient and sustainable alternative to diesel-based propulsion. By adopting fuel cell-battery hybrid systems, investing in hydrogen refueling infrastructure and ensuring compliance with stringent safety standards, the maritime industry can accelerate the transition toward decarbonized sea mobility.

Policymakers, shipbuilders, and ferry operators must work collaboratively to expand hydrogen availability, lower costs and refine safety regulations. As technology matures and economies of scale improve, hydrogen ferries will become an integral part of sustainable maritime networks, supporting climate goals and green transportation initiatives worldwide.

11 Conclusions

The transition to hydrogen-fueled passenger ferries represents a paradigm shift in maritime transportation, offering a zero-emission alternative to conventional fossil-fuel powered vessels. This report has provided a comprehensive analysis of the technical, economic, environmental and regulatory factors influencing the adoption of hydrogen propulsion for ferry services. Through an in-depth assessment of fuel cell technology, propulsion architectures, energy system layouts, and safety aspects considerations, it has become evident that hydrogen has the potential to reshape the maritime sector, aligning with international decarbonization goals such as those set by the International Maritime Organization (IMO) and the European Green Deal.

The multi-criteria analysis performed clearly shows that PEM fuel cell (PEMFC) systems outperform other technologies, with the top three positions across all storage methods. The best-performing configuration is PEMFC with compressed hydrogen (350 bar), followed closely by PEMFC with LOHC and liquid hydrogen. This reflects the maturity, efficiency, and integration flexibility of PEMFCs in marine applications.

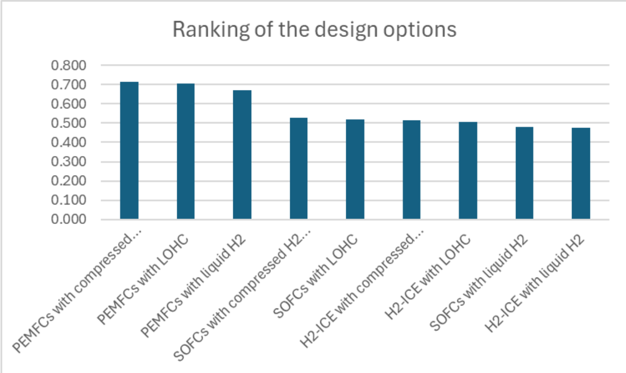

Figure 11-1 Ranking of the evaluated design options

SOFCs rank in the middle, showing moderate performance, likely limited by lower readiness and slower dynamics. Hydrogen ICEs consistently rank lowest, mainly due to lower efficiency, emissions concerns and technology readiness.

Overall, PEMFCs combined with compressed H_2 present the most balanced and effective solution among the options evaluated.

A critical barrier to widespread hydrogen adoption remains the lack of refueling infrastructure and the high cost of hydrogen production. While green hydrogen produced via electrolysis provides a fully carbon-free energy source, current production capacity and distribution networks remain limited and expensive. Public-private partnerships, government subsidies and investments in hydrogen supply chains will be essential to overcoming these challenges. Hydrogen-fueled ferries will only achieve full market competitiveness if supported by a scalable refueling ecosystem and cost reductions through economies of scale.

Safety and regulatory compliance are paramount in the deployment of hydrogen-powered vessels. Hydrogen's flammability, low ignition energy, and rapid diffusion properties require advanced leak detection systems, explosion-proof enclosures, and emergency response protocols. International regulations such as the IMO IGF Code, SOLAS, and classification society guidelines provide a framework for safe hydrogen fuel handling, but additional standardization efforts and regulatory updates will be necessary to fully accommodate hydrogen as a mainstream maritime fuel.

Moving forward, it is imperative that ferry operators, policymakers, shipbuilders, and hydrogen producers collaborate to establish a well-defined roadmap for hydrogen adoption in maritime transport. Investment in green hydrogen production, regulatory support for port infrastructure upgrades and continued advancements in fuel cell efficiency will dictate the pace of hydrogen integration in the sector.

In conclusion, hydrogen-powered passenger ferries present a transformative opportunity for the maritime industry, offering an efficient, scalable, and truly zero-emission alternative to traditional fuel sources. As regulations tighten, hydrogen technology matures and the economic case for clean shipping strengthens, hydrogen will play a crucial role in the future of sustainable maritime transport.

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