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Risk management strategies for the use of ammonia and hydrogen as marine fuels

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Abstract. This paper aims to identify risk management strategies for ammonia and hydrogen as alternative maritime transport fuels. Maritime transport is a significant contributor of greenhouse gas which faces rising regulatory demands to reduce its carbon footprint. The research investigates the safety risks of ammonia and hydrogen by studying their toxic properties and flammability characteristics and the operational and bunkering safety concerns. The research uses risk assessment frameworks together with failure mode and effects analysis and hazard identification techniques to determine potential risks and suitable mitigation measures. The research shows that both fuels require strict safety measures and trained crew and monitoring systems because of their different physical and chemical characteristics. The research establishes that an integrated risk management framework must be adopted to enable safe and sustainable ammonia and hydrogen adoption in maritime operations which will help the industry meet worldwide decarbonization targets.

Keywords: ammonia; hydrogen; alternative fuel; risk management; decarbonization.

1. Introduction

The maritime transport sector functions as a vital element of worldwide trade because it handles 80% of all traded volumes while supporting international supply chain operations. The maritime sector generates about 3% of worldwide greenhouse gas emissions which obstructs global efforts to reduce carbon emissions (Melnik et al., 2023; Torreglosa et al., 2022). The International Maritime Organization (IMO) has established new regulations about marine fuel sulfur content while demanding maritime decarbonization efforts (López et al., 2024; Torreglosa et al., 2022). The shipping industry needs immediate solutions to find and adopt alternative fuels which solve both economic feasibility and environmental sustainability problems. The decarbonization strategies focus on alternative fuels which include ammonia and hydrogen together with multiple biofuel options. The combustion of blue and green ammonia produces zero carbon emissions but generates some reactive nitrogen emissions that create environmental issues (Wong et al., 2024; Drazdauskas & Lebedevas, 2024). The maritime transport sector can utilize hydrogen as a promising solution because of its beneficial energy properties (Ampah et al., 2024; Motlagh et al., 2023). These fuels enable researchers to reshape the maritime industry's energy mix which supports worldwide climate change reduction targets.

The maritime sector require immediate action to achieve carbon neutrality so the industry must accept alternative fuels for its operations. The carbon-free combustion characteristics of ammonia (NH₃) combined with its compatibility with conventional engine systems make it a highly valuable fuel alternative according to Hansson et al. (2020) and Mallouppas et al. (2022). The shipping industry produces substantial global emissions which means technological progress in ammonia fuel systems will help meet Environmental targets through their required greenhouse gas emission reductions (Chen et al., 2023; Gerlitz et al., 2022). The production methods of green ammonia that use renewable energy resources create lower lifecycle emissions than conventional fossil fuels according to Prause et al. (2022). The maritime industry recognizes ammonia as a fundamental alternative fuel because it could replace 70% of marine fuel consumption by 2035 thus supporting sustainable maritime logistics and addressing operational and infrastructure challenges (Hansson et al., 2020; Bernardini et al., 2022). The shipping industry can achieve significant decarbonization through the use of hydrogen (H₂) because it contains high energy density and produces zero emissions during combustion (Krantz et al., 2023; Bernardini et al., 2022). Hydrogen use in fuel cells and internal combustion engines (ICEs) works

together to enhance energy efficiency while reducing pollutant emissions according to Tornatore et al. (2022). Hydrogen proves to be a key component for reaching the IMO's carbon reduction targets through its ability to replace conventional fuels (Lee et al., 2024; Pothaar et al., 2022). Hydrogen adoption for maritime fuel use requires solutions for storage and distribution systems and major investment in new infrastructure (Chen et al., 2023; Gerlitz et al., 2022). The challenges of hydrogen adoption can be overcome through research developments in renewable energy-based electrolysis methods which will establish hydrogen as a sustainable maritime operational fuel (Xu et al., 2022).

The maritime industry needs to solve multiple safety and risk management issues before it can safely adopt ammonia and hydrogen as marine fuels. The hazardous nature of ammonia includes toxic and corrosive properties and skin and respiratory system irritation while hydrogen presents high flammability risks that create explosive air-hydrogen mixtures (Venkadasalam, 2023; Fan et al., 2021; Duong et al., 2024). The IGF Code serves as a fundamental tool for risk management because it provides detailed safety standards for ships that use alternative fuels through its regulations about ship design and construction and operational requirements (Venkadasalam, 2023). The bunkering process of ammonia creates specific safety risks because toxic gas dispersion can occur and leaks can start fires (Fan et al., 2021). The unpredicted toxic gas dispersion during ammonia bunkering operations requires safety zones and complete emergency response plans because quantitative risk assessments show it poses serious safety risks (Fan et al., 2021; Duong et al., 2024).

The risk management challenges for hydrogen are equally complex because of its properties as a lightweight and highly flammable gas (Rheenen et al., 2023). Rheenen et al.'s research indicates that effective hazard identification processes are crucial for evaluating the safety risks of hydrogen systems on ships. The development of hydrogen carriers introduces additional safety risks because their chemical properties affect both their operational performance and storage and usage risk levels on vessels (Rheenen et al., 2023). Specialized training programs for crew members who handle ammonia and hydrogen fuel systems need to be developed to address the specific knowledge gaps that are necessary for operational and emergency response protocols to mitigate the associated risks (Hrenov et al., 2023). The experience from pilot projects and initial operational experiences should be systematically leveraged to refine safety guidelines, inform industry best practices, and enhance regulatory frameworks surrounding ammonia and hydrogen as fuels for maritime operations (Forum, 2020). A comprehensive risk management strategy that includes engineering, regulatory, and operational dimensions is essential for ensuring the successful and safe adoption of these promising fuel alternatives in the maritime sector.

The main objective of this research is to develop and evaluate comprehensive risk management strategies for the use of ammonia and hydrogen as marine fuels with a focus on safe deployment and integration into the maritime sector. This study aims to identify the potential hazards and risks associated with both fuels by using hazard identification methodologies and quantitative risk assessment techniques to gain a detailed understanding of the unique safety challenges.

2. Methodology

The research uses a complete methodology to develop risk management approaches for marine fuel use of ammonia and hydrogen through the Risk Assessment Framework and Failure Mode and Effects Analysis (FMEA) and Hazard Identification (HAZID) techniques. The Risk Assessment Framework provides a systematic approach to evaluate potential hazards from ammonia and hydrogen fuels including their toxic properties and storage requirements. The system uses this approach to stop accidents by eliminating hazards while performing required safety measures. The FMEA technique will help identify system performance failure modes and their causes and effects to determine risk priority based on severity and occurrence likelihood. The HAZID methodology enables the identification of operational and environmental risks during ammonia and hydrogen handling and storage and bunkering through expert consultations and structured brainstorming sessions. The qualitative analysis method HAZID uses expert brainstorming to identify risks according to Kim (2022).



Figure 1. Research Process Diagram

The selection of experts for a workshop about this subject requires participants who possess expertise in fuel technology and combustion processes as well as safety assessments and regulatory frameworks. The combination of these expert bodies will enable a thorough investigation of safety risks in marine applications that use ammonia and hydrogen. Risk management and safety assessment professionals are also vital. The workshop requires participants who specialize in alternative fuel safety implications and have written reviews about maritime ammonia safety to provide necessary insights about regulatory compliance and safety protocols and emergency response strategies. Table 1 lists the expert group. Their expertise will aid in assessing and minimizing the potential hazards associated with marine bunkering processes of ammonia and hydrogen, which poses different safety concerns due to its flammability.

Table 1. HAZID expert team

Job title	Role/Expertise	Company
Marine fuels specialist	Subject matter expert	Shipping Company
Marine fuels specialist	Regulatory expert	Bunker Trader
Technical Director	Subject matter expert	Shipping Company
Technical Superintendent	Subject matter expert	Shipping Company
Senior manager SQMS	HAZID facilitator/Risk assessment	Shipping Company
Senior manager SQMS	Risk assessment	Shipping Company
Senior manager SNS	Safety of Navigation expert	Shipping Company
Superintendent SNS	Safety of Navigation expert	Shipping Company
Researcher	Risk assessment	Research institute
Researcher	Observer/Process design	Research institute

2.1. Hazard Identification (HAZID) process

2.1.1. Identification of HAZID categories

The initial step requires the selection of ammonia and hydrogen categories for marine fuel applications. Categories encompass particular systems and equipment and operational tasks and environmental contexts that may produce hazards. The initial stage holds the greatest importance because it establishes the basis for creative hazard identification through process decomposition (Jabbari et al., 2021). The identified categories correspond to specific locations including fuel storage systems and distribution interfaces and combustion engines.

2.1.2. Briefing

A briefing about each hazard must be conducted after the categories have been identified. The briefing should explain the purpose of each category and the involved processes and their role in the operational framework to enable systematic hazard evaluation by participants. The briefing will deliver specialized knowledge about how each direction interacts with potential hazards. The session briefings will be delivered by professionals from relevant domains to provide participants with complete understanding of the systems they will analyze.

2.1.3. Identification of Hazards and Hazardous Events

The identification of potential hazards for each category requires systematic methods including brainstorming and expert interviews. The recognized hazards may include, but are not limited to, leaks, explosive reactions, toxicity, and operational failures. The researches of Jabbari and Dadgar confirm that the HAZID methodology is essential for initial hazard identification, as it allows for identifying processes and tasks that present risks to workers, equipment, and the environment (Jabbari et al., 2021; Dadgar, 2021).

2.1.4. Identification of Causes & Consequences

The identification of hazards requires a detailed analysis of their potential causes and consequences. The assessment process requires evaluation of scenarios that could result in hazardous events (e.g., equipment failure, human error) and their potential consequences (e.g., environmental damage, safety incidents).

2.1.5. Identification of Preventive and Mitigating Safeguards

The identification of hazards and their causes requires the development of preventive and mitigating controls. The proposed measures should include engineering controls and safety protocols and emergency plans and training. The literature highlights the necessity of implementing preventive measures properly to reduce the risks that were identified during HAZID sessions (Chen et al., 2023). The assessment becomes more thorough when safety engineering and environmental protection experts participate in the process.

2.1.6. Risk Ranking

Finally, the identified hazards should be ranked to prioritize which require immediate attention concerning their risk. The risk ranking process begins with a comprehensive list of identified hazards from the HAZID conducted in previous sections. Each hazard that can result in a hazardous event while using ammonia and hydrogen as fuels will be assessed for its likelihood and consequences presented on Table 2 and Table 3. Risk ranking is typically done by evaluating the likelihood of occurrence and severity of consequences of each identified hazard as per Equation 1. This systematic ranking allows stakeholders to focus their resources efficiently on the highest risks.

$$Risk(R) = Likelihood(L) \times Consequence (C) \quad (1)$$

Table 2. Likelihood Rating

Level	Description	Probability	Example in Maritime Transport
1 - Rare	Extremely unlikely, may occur only under extreme circumstances	< 1 time in 10 years	Major fuel spill from a double bottom in case of a collision
2 - Unlikely	May occur, but rarely	1 time in 5-10 years	Minor ammonia leak from a valve due to improper operation
3 - Possible	May occur occasionally	1 time in 1-5 years	Minor damage to a cryogenic hydrogen tank

4 - Likely	Expected to occur occasionally	1 time per year	Corrosion of NH ₃ pipelines requiring replacement
5 - Frequent	Expected to occur regularly	Several times per year	Small hydrogen leaks in the pipeline system during operation

Table 3. Consequences Rating

Level	Description	Consequences	Example in Maritime Transport
1 - Insignificant	No serious impact, minor damage, negligible consequences	Small damage that does not affect safety or operations	Minor fuel loss with no significant impact on the ship or crew
2 - Minor	Slight impact on safety or efficiency, but easily repairable	Minor damage that does not require stopping the ship or operations	Unnoticeable hydrogen leaks that do not lead to incidents
3 - Moderate	Possible impact on safety or the environment, requiring repairs or operational stoppage	Damage requiring repairs, but without serious consequences for the crew	Partial damage to ammonia pipelines, not leading to an incident
4 - Major	Significant impact, serious damage to the ship or crew, may lead to prolonged operational disruptions	Severe damage or casualties requiring a long recovery time	Ammonia tank explosion, damage to part of the ship
5 - Catastrophic	Potential for major losses, including fatalities and/or severe environmental damage, permanent operational disruptions	Severe loss of the ship, crew fatalities, environmental disasters	Massive explosions and fires, ship destruction, crew fatalities

The scoring system presents an assessment of the comparative risks that exist between different scenarios. The risk scores were translated into a risk matrix which classified the resulting risks into three categories as shown in Table 4:

Low Risk (Green): Scores 1-4. The risk is acceptable and no extra preventive or mitigation measures are required beyond the standard operating procedures.

Medium Risk (Yellow): Scores 5-9. The risk requires additional measures to reduce it and suggested strategies include improved safety protocols, training and equipment checks.

High Risk (Red): Scores 10-25. The risk is unacceptable and requires immediate corrective actions to mitigate risks.

Table 4. Risk Matrix

Consequence / Likelihood	1 - Rare	2 - Unlikely	3 - Possible	4 - Likely	5 - Frequent
5 - Catastrophic	M (Medium)	H (High)	H (High)	H (High)	H (High)
4 - Major	M (Medium)	M (Medium)	H (High)	H (High)	H (High)
3 - Moderate	L (Low)	M (Medium)	M (Medium)	H (High)	H (High)
2 - Minor	L (Low)	L (Low)	M (Medium)	M (Medium)	H (High)
1 - Insignificant	L (Low)	L (Low)	L (Low)	M (Medium)	M (Medium)

3. Results

3.1. Identification of main categories and hazards

The expert group systematically identify potential hazards associated with the use of ammonia and hydrogen as a marine fuel. Through workshops and discussions, four main risk categories were defined: physicochemical properties, technical risks, operational risks presented in Table 5 for Ammonia and Table 6 for Hydrogen.

Table 5. HAZID Analysis of Ammonia (NH₃) as Marine Fuel

Category	Hazard	Cause	Consequence	Consequence Rating (1-5)	Likelihood Rating (1-5)	Risk Rating
Physico-chemical Properties	High toxicity when inhaled	Gas leakage from storage or transport systems	Severe health effects, fatal at high concentrations	5 (Catastrophic)	3 (Possible)	H (High)
	High corrosiveness to metals and plastics	Long-term exposure of materials to ammonia	Equipment damage, leaks, accidents	4 (Major)	4 (Likely)	H (High)
	High solubility in water → formation of toxic solutions	Ammonia spill into the marine environment	Severe environmental impact, water pollution	3 (Moderate)	3 (Possible)	M (Medium)
	High pressure for liquefaction (requires special tanks)	Improper storage or tank failure	Risk of explosion or toxic gas release	3 (Moderate)	3 (Possible)	M (Medium)
Technical Risks	Leakage from storage systems due to corrosion or mechanical failures	Poor maintenance or defective materials	Inhalation of toxic vapors, explosive atmosphere	5 (Catastrophic)	3 (Possible)	H (High)
	Potential for thermal decomposition at high temperatures	Overheating or contact with incompatible materials	Chemical reactions, risk of leakage	4 (Major)	2 (Unlikely)	M (Medium)
	Material degradation (brittleness, cracking)	Long-term exposure of pipelines and tanks to ammonia	Mechanical failures, risk of leakage	3 (Moderate)	3 (Possible)	M (Medium)
Operational Risks	Leakage during bunkering or fuel transfer	Poor connections, defects in transfer systems	Air pollution, crew safety risk	5 (Catastrophic)	3 (Possible)	H (High)

	Need for specialized safety procedures	Lack of standardized protocols or improper training	High accident risk due to operator errors	4 (Major)	4 (Likely)	H (High)
	Lack of crew training for ammonia handling	Insufficient qualification and preparation	Higher likelihood of human errors and incidents	4 (Major)	3 (Possible)	H (High)
	Potential freezing of pipelines and valves	Low temperatures of liquefied ammonia	Reduced fuel flow, system failures	3 (Moderate)	3 (Possible)	M (Medium)

Table 6. HAZID Analysis of Hydrogen (H₂) as Marine Fuel

Category	Hazard	Cause	Consequence	Consequence Rating (1-5)	Likelihood Rating (1-5)	Risk Rating
Physico-chemical Properties	High flammability and explosiveness	Hydrogen leakage from storage or pipelines	Fire or explosion, severe structural damage, crew injuries	5 (Catastrophic)	4 (Likely)	H (High)
	Extremely low temperature in liquid form	Contact with skin or materials	Frostbite, material embrittlement, equipment failure	4 (Major)	3 (Possible)	H (High)
	Small molecule size → high permeability and leakage risk	Hydrogen diffusion through seals and joints	Loss of fuel, increased explosion risk	3 (Moderate)	4 (Likely)	H (High)
	Wide explosive range in air (4%-75%)	Uncontrolled release and ignition sources present	Large-scale explosion, severe vessel damage	5 (Catastrophic)	3 (Possible)	H (High)
Technical Risks	High-pressure storage requirements	Failure of high-pressure tanks or valves	Sudden hydrogen release, explosion risk	5 (Catastrophic)	3 (Possible)	H (High)

Operational Risks	Material degradation (hydrogen embrittlement)	Long-term exposure of metals to hydrogen	Cracking of pipelines, mechanical failure	4 (Major)	3 (Possible)	H (High)
	Cryogenic storage challenges	Insufficient insulation or equipment failure	Hydrogen loss, frost damage, operational difficulties	3 (Moderate)	3 (Possible)	M (Medium)
	Risk of ignition during bunkering	Electrostatic discharge, improper handling	Fire, explosion, severe damage to vessel	5 (Catastrophic)	3 (Possible)	H (High)
	Lack of crew training on hydrogen handling	Inadequate knowledge of safety procedures	Increased likelihood of human errors, accidents	4 (Major)	4 (Likely)	H (High)
	Hydrogen venting and purging risks	Improper venting procedures	Accumulation of flammable gas, risk of explosion	4 (Major)	3 (Possible)	H (High)
	Limited infrastructure for refueling	Insufficient hydrogen bunkering facilities	Operational delays, logistical complications	3 (Moderate)	4 (Likely)	H (High)

The risk assessment of ammonia and hydrogen as marine fuels reveals that these two energy carriers present similar major challenges despite their different physical and chemical characteristics. In both cases, the primary risks are related to the high danger to human health and safety, complex storage and transport requirements, as well as serious regulatory and infrastructure barriers. The main differences come from the specifications of the fuels. The toxic and corrosive nature of ammonia requires strict protective measures for personnel and equipment while hydrogen's high flammability creates explosion risks. The end result remains the same for both fuel types because they require substantial technical and operational measures to ensure safe and effective use.

Regardless of the differences in their physical characteristics, all identified risks are high and require urgent control and management measures. The implementation of these fuels faces challenges because of non-existent international standards and the requirement for specialized crew training and limited port infrastructure which could result in severe incidents if not resolved promptly.

The safe and sustainable use of these fuels requires immediate development of integrated risk management strategies.

3.2. Development of risk management strategies

The implementation of ammonia and hydrogen as marine fuels requires multiple risk management strategies which include engineering and technical measures alongside operational procedures and digital technology applications. The three categories work together to improve maritime operational safety and efficiency.

3.2.1. Engineering and Technical Measures

The development of new materials and fuel system designs plays a crucial role in enhancing both safety and operational efficiency when using ammonia and hydrogen. Research shows that strong materials must be developed to handle the corrosive and explosive properties of these fuels. The implementation

of leak monitoring systems together with automated risk detection systems represents a fundamental requirement. Real-time analysis through automated monitoring systems enables immediate responses to detected leaks which are essential for preventing catastrophic failures.

3.2.2. Operational Procedures and Training

The development of operational protocols for ammonia and hydrogen fuel handling represents a necessary step to reduce associated risks. Crew members need to undergo rigorous training programs that teach them the essential skills needed to handle these fuels safely on board. Specialized training programs decrease human mistakes which stand as the primary cause of maritime accidents. The combination of detailed procedures with thorough training produces better decision-making abilities during dangerous situations which results in improved maritime safety.

3.2.3. Use of Digital Technologies for Risk Management

Digital technologies are revolutionizing maritime risk management practices through their implementation. Digital Twins enable the simulation of system behavior in virtual environments to predict potential emergencies and evaluate response strategies before actual incidents take place. Real-time risk analysis systems that use automated detection through machine learning identify operational anomalies which signal potential risks so operators can take prompt action. These technological advancements improve operator situational awareness while enhancing the reliability and safety of maritime operations that use ammonia and hydrogen as fuels.

4. Conclusions

The maritime sector can achieve major greenhouse gas emission reductions through the use of ammonia and hydrogen as marine fuels. The study stands out because it provides detailed risk management approaches for these fuels which current literature has not fully explored. The existing body of research has primarily studied environmental advantages and operational efficiency of these fuels but this study emphasizes the necessity to handle safety risks including toxic and flammable properties. This study merges technical and operational aspects to advance the growing knowledge base about safe implementation of ammonia and hydrogen fuels in maritime operations.

The research contains significant limitations because it fails to include all possible operational situations and does not address all regional regulatory variations that impact fuel consumption. The study's limitations demonstrate the need for additional research that would analyze pilot project data across different maritime settings and various operational environments and regulatory frameworks. Future research should address these gaps to improve the strength of risk assessments and develop safety management approaches that work across all maritime alternative fuel applications.

The research findings demonstrate the need for a complete framework that requires thorough training for fuel-handling crews and advanced monitoring systems and specialized safety regulations which account for ammonia and hydrogen characteristics. These safety measures will reduce risks effectively to support safe maritime operations which will enable cleaner fuels to advance maritime sustainability. The maritime industry will achieve global decarbonization targets through the strategies outlined in this study which will promote the widespread adoption of ammonia and hydrogen as marine fuels.

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- Conceptualization: I.D. and A.H. (author's name initials)
- Methodology: A.H.
- Investigation: I.D. and A.H.
- Writing original draft: I.D.
- Writing review and editing: A.H.
- Supervision: I.D. and A.H.

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