AMMONIA: A CLEAN FUEL FOR A CLEANER FUTURE

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Abstract

This paper explores the potential of ammonia as a clean fuel for the maritime industry, aiming to achieve the International Maritime Organization's (IMO) ambitious decarbonisation targets. A SWOT analysis is conducted to assess the Strengths, Weaknesses, Opportunities, and Threats associated with ammonia adoption as marine fuel.

Ammonia boasts advantages like zero CO_2 emissions, and higher energy density compared to hydrogen (reducing storage space needed). However, there are challenges such as the high reliance on fossil fuels for current ammonia production, the need for stricter safety protocols and crew training, and potential engine modifications for existing ships.

On the other hand, developing a global green ammonia supply chain presents a significant opportunity for economic development, particularly for countries rich in renewable energy sources. Technological advancements in storage solutions and ammonia's ability to act as a hydrogen carrier further enhance its appeal.

Some of the identified threats are the requirement of significant investments in infrastructure, ship modifications, and green ammonia production facilities. Standardized regulations and public acceptance regarding ammonia safety remain hurdles to overcome. The emergence of competing zero-carbon alternatives also presents a potential threat.

Safety considerations of using ammonia as fuel require studies to identify potential hazards and risks and what safeguards should be implemented to prevent or mitigate the major hazards. One of the key preventive measures is crew training. Standardized training programs focused on the properties, safe handling procedures, and emergency response protocols for ammonia as a fuel are crucial.

1 INTRODUCTION

Can shipping become a reliable source of demand for clean transport solutions? Will it be possible to reach the Net Zero Emissions (NZE) Scenario by 2050? According to IEA, in 2022 international shipping accounted for about 2% of global energy-related CO_2 emissions. Therefore, it is necessary to take consistent steps towards decarbonisation and emission reduction. It is calculated that it requires an almost 15% reduction in emissions from now to 2030. IMO's initial strategy on reducing GHG emissions from IMO ships (Resolution MEPC.304(72)) stablished a path for contributing to global efforts to address GHG emissions in line with goals set out in the Paris Agreement and the UN 2030 Agenda for Sustainable Development and its SDG 13: 'Take urgent action to combat climate change and its impacts'. This resolution includes the ambition to slash ocean-vessel emissions by at least 50% by 2050 (compared to 2008). This requires that the international maritime industry set a course towards cleaner fuels, that are zero or low-carbon fuels. One strong candidate to

Ammonia is a strong candidate to lead this green transformation. There are several initiatives worldwide seeking to tap ammonia to power shipping. Compared to liquid hydrogen, ammonia boasts a higher energy density per unit volume. Additionally, ammonia storage requirements are significantly less demanding, with a storage temperature of -33°C or moderate pressure (10 bar) compared to the -253°C required for liquid hydrogen. The storage of chilled liquid ammonia eliminates the need for bulky pressurized tanks for concentrated hydrogen gas. Compared to hydrogen, ammonia boasts two more advantages for shipboard use. First, it requires 46% less on board storage space, a significant benefit for optimizing ship design and cargo capacity. Second, ammonia possesses a narrower flammability range and a higher ignition temperature, translating to a lower fire risk compared to hydrogen (Ash & Scarbrough, 2019).

Ammonia, unlike other proposed fuels, benefits from proven and widely used production technologies, which facilitates its integration into existing infrastructure. In addition, its familiarity in the maritime industry, as a product commonly transported in gas carriers, has enabled the development of robust safety standards and regulations.

Compared to other fuels, total GHG emissions can be reduced by around 85% when using green ammonia. Emissions such as sulphur dioxide, carbon monoxide, heavy metals, particulate matter and polycyclic aromatic hydrocarbons (PAHs) are also reduced (in some cases almost to zero).

However, the adoption of ammonia as a green marine fuel must consider key issues:

- Sustainable production: ammonia must come from 'green' sources, such as electrolysis driven by renewable energies, such as direct solar energy, to ensure true decarbonisation. For ammonia to be a truly carbon-free fuel source, it is needed to develop methods for producing it using renewable energy.

- Availability: Currently the production capacity of green ammonia is low. For ammonia to become an alternative to conventional marine fuels it must be available globally, as shipping is international. So, it is crucial to develop a green ammonia supply chain at the scale that the international shipping requires. To do so there are technical and economic barriers to overcome, but it also means a potential investment opportunity.

- Regulation and safety: The use of ammonia as a fuel requires specific regulations, safety protocols and thorough training of personnel. The toxic properties of ammonia must be addressed to ensure safe use and minimise potential risks.

2 STRENGTH, WEAKNESS, OPPORTUNITIES AND THREATS

Ammonia (NH_3), widely used in the chemical industry and best known as the backbone of fertilizer, holds a promising future as a marine fuel. Rich in hydrogen, ammonia can be readily adapted for fuel use, and when burned, emits only water steam, a significant advantage over traditional fossil fuels that contribute to CO_2 emissions. This SWOT analysis dissects the key strengths, weaknesses, opportunities, and threats (SWOT) associated with adopting ammonia as a marine fuel.

Strengths	**Weaknesses**
• Zero Carbon Emissions (on a tank-to-wake basis) and lower toxic emissions (SO_2, metals, particulate matter, polycyclic aromatic hydrocarbons, PAH), and zero NO_X in low temperature fuel cells. • The chemical industry already possesses a well-developed infrastructure for ammonia production, storage, and transportation. • Compared to alternative clean fuels like hydrogen, ammonia boasts a higher energy density per unit volume, requiring less storage space. That allows ships to store enough fuel for voyages lasting several weeks • It does not require cryogenic storage (unlike hydrogen). • It can be used in modified internal combustion engines without the need for intricate on board processing equipment. • Ammonia can be used in engines and fuel cells. • Fire risk and risks from cryogenic burns are lower than for liquid hydrogen or liquefied natural gas.	• Ammonia requires 4.1 times as much space as fossil fuels • Ammonia production methods heavily rely on fossil fuels, so it would offer little or no environmental benefits if used as a shipping fuel. • The cost of producing green ammonia is sensitive to the price of electricity. • Ammonia is toxic and flammable, necessitating stricter safety protocols and crew training for handling and storage on board vessels. • Safety principles and systems would need to be arranged on ships. • Existing ship engines need significant modifications or complete overhauls to accommodate ammonia as fuel. • Ammonia contains only about one-third the energy per volume compared to traditional heavy fuel oil (HFO) or marine gas oil (MGO), necessitating larger storage tanks or more frequent refuelling. • When used in internal combustion engines, ammonia produces nitrogen oxides that must be reduced, for instance with Selective catalytic reduction SCR (which uses ammonia or urea). • When used in combustion engines, ammonia might require a pilot fuel • Although classification societies have introduced provisional rules and guidelines to support the adoption of ammonia-fueled ships, there the absence of regulations for using ammonia as a fuel at national, regional, and international levels presents a significant barrier to its implementation.

Opportunities:	**Threats**
• The extensive use of ammonia in fertilizers has fostered a well-established global market, facilitating its production and shipping it on a global scale. • Developing a global network of ammonia bunkering stations can address concerns about refuelling frequency. • The creation of a green ammonia supply chain can be an opportunity for a worldwide sustainable economic development and distribution of bunkering infrastructure, especially for developing economies with a high potential renewable energy. • The development of green ammonia production methods (as electrolysis) utilizing renewable energy sources (solar or wind power) can led towards a marine fuel truly emissions free on a lifecycle bases (well-to-wake basis). • The existence of reliable sources of demand can warrant the significant upfront costs associated with large-scale. • Technological advancements in on board storage solutions can mitigate the lower energy density of ammonia compared to fossil fuels. • Ammonia can act as a convenient carrier for hydrogen, a clean fuel for future propulsion technologies. Thus, it can serve as both a fuel and a hydrogen carrier offers flexibility for the future of clean shipping technologies. • According to engines manufactures, it is possible to upgrade some existing dual-fuel engines to operate on ammonia. • Existing regulations governing the storage, transport, and use of anhydrous ammonia on land and at sea provide a framework to expedite its adoption as a marine fuel. • Policy and regulatory support from governments is spurring research and incentivizing infrastructure development. • Collaboration between different stakeholders (shipbuilders, fuel producers, and regulatory bodies) can expedite the transition to ammonia-powered ships. • The associated risks of ammonia can be mitigated establishing safety protocols and procedures.	• The transition to ammonia may require significant investment in new infrastructure, ship modifications, and potentially, green ammonia production facilities. • A lack of clear and standardized regulations regarding ammonia use in shipping can hinder widespread adoption. • Potential concerns surrounding the safety of ammonia transportation and storage could pose a barrier to public acceptance. • While initial costs will likely be higher, early adopters of zero-carbon fuels like ammonia will face a competitive disadvantage compared to those using traditional fossil fuels. To overcome this hurdle and avoid penalizing these pioneers, a robust mechanism is needed to incentivize the development and deployment of zero-carbon fuels. • Other zero-carbon alternatives, such as biofuels or electro-fuels, may emerge as strong competitors to ammonia. • Adapting existing regulations and safety protocols for handling and storing ammonia on board ships may require time and resources.

Table 1 Ammonia as a marine fuel. SWOT analysis.

3 AMMONIA AS A MARINE FUEL: SAFETY CONSIDERATIONS

Ammonia is a colourless gas with a pungent odour, highly toxic at low concentrations to both people and marine life. Its powerful smell can be a physical irritant and its corrosive properties can cause skin and eye damage. It is lighter than air (except in very humid environments). In case of a spill, ammonia would float on water, dissolving into ammonium hydroxide and releasing gaseous ammonia. Wind dispersal and water conditions would determine the impact on local air and aquatic life. It has a lower flammability risk compared to other fuels due to its slow flame speed and narrow flammability range.

While ammonia offers promise as a clean-burning marine fuel, it has safety risk that should be acknowledge and manage. Safety regulations for using ammonia as marine fuel are still under development, although there are different teams working in early-stage risk assessments to use ammonia as a maritime fuel. Those initiatives include the participation of multi-disciplinary teams including shipowners, ship classification societies, shipyards and engine manufactures.

It is important to identify which hazards related to the use of the ammonia on board as a fuel and determine the potential consequences of the hazards. The causes, consequences and existing safeguards analysis will help to improve future ship design and develop risk mitigation measures to reduce the estimated safety risk. As different vessel types will present unique potential hazardous scenarios, depending on their general arrangement and specific design features, it should be necessary further safety assessments.

Risk assessments for vessels utilizing low-flashpoint fuels, as required by the IGF Code, should be conducted using established techniques such as HAZID (Hazard Identification) or FMEA (Failure Mode and Effects Analysis), as aligned with IACS Recommendation No. 146. This assessment should consider the risks specific to ammonia, including those listed in paragraph 3.2 of IACS Rec. 146, along with the following:

- Loss of function
- Component damage
- Fire
- Explosion
- Collision
- Grounding
- Intoxication
- Chemical burning
- Pollution
- Variations of bunkered ammonia fuel characteristics (temperature)
- Rollover.

To ensure the safe and efficient use of NH_3 as a marine fuel key focus area should be studied, that are the general arrangement of vessels, detailing how NH_3 fuel storage is managed and the specific arrangements involved, ammonia fuel supply and vapour-handling systems, covering the entire process from fuel storage to machinery spaces. In addition, the arrangement of NH_3 fuel in both the fuel handling room and engine room should be scrutinized, with particular attention to the general arrangement and ventilation of these spaces. Main engine safety concepts and their integration into the vessel are crucial, alongside the classification plans for hazardous areas. The ventilation systems and vents associated with stored NH_3 fuel, the fuel-supply system, machinery space, and consumer areas should also be covered, as well as the ammonia fuel-bunkering arrangement and the bunkering process (the transfer of fuel should be conducted safely). Furthermore, hazard studies might cover safety systems, gas detection, and firefighting arrangements. It includes procedures for purging or rendering ammonia inert, and assesses the impact of cargo storage. The emergency escape and rescue arrangements should also be detailed to ensure comprehensive safety and preparedness.

4 TRAINING AND CERTIFICATION PROGRAMS

While the maritime industry already transports ammonia as cargo and utilizes it for refrigeration on some vessels, widespread use as a fuel requires the development of standardized procedures. Crew would need to develop competencies for safely handling ammonia as a fuel, therefore training on its properties and safe handling will be crucial. Regulations about training and learning programs focused on ammonia fuel safety are needed. The key is to educate seafarers about handling, storage, and safety precautions and protocols specific to ammonia-fuelled ships.

The crew training should cover:

- Physical and chemical characteristics of ammonia.
- Potential hazards (toxicity, corrosion, flammability). It is necessary to understand ammonia's corrosion potential, its incompatibility with certain materials, and the potential failure mechanisms that can arise. Training should also cover mitigation strategies to minimize the occurrence of these issues. Crew training also should emphasize the dangers of gas expansion, particularly in confined spaces, as with any liquefied gas, there's a risk of rapid expansion upon release.
- Workplace Exposure Limits and self-protection to avoid exposure during operational / maintenance tasks.
- Regulations and guidance.
- Safe handling procedures.
- Leak detection and spill management.
- Types of tank containment systems.
- Bunker delivery methods.
- Safe Bunkering Operations and interactions with the port and other shore side parties.
- Correct storage and management of fuel tanks. Events as an over-pressurisation of fuel storage tank can also lead to ammonia leaks.
- Crew training for operating new equipment, safety devices, and procedures associated with ammonia-fuelled vessels. This includes training on vapour and boil-off gas management systems.
- Emergency response (either on an open deck or in an enclosed space) and firefighting.
- The bunkering operation and simultaneous operations considerations.
- Safe practices in utilizing venting and ventilation with ammonia.
- Especially shift in engineers will need a deeper understanding of process control systems with a growing reliance on automation.
- Higher automation might require some crew members to develop competencies similar to those of an Electro-Technical Officer (ETO).
- The role for a Gas Engineer might be created (like in other vessels such as tankers and LNG ships).
- Crew members directly handling ammonia must be informed and provided with specialized Personal Protective Equipment (PPE), like portable gas detectors, gastight suits and self-contained breathing apparatus (SCBA). For refrigerated ammonia, thermal protection may also be necessary.
- Decontamination of equipment and personnel using readily available water.
- Specific first-aid requirements (oneself or others) for ammonia used as a marine fuel. This issue points out the need to review and potentially update the IMO/ILO/WHO Medical First Aid Guide (MFAG) to encompass the specific first-aid requirements for ammonia used as a marine fuel.

Industry and regulatory bodies are collaborating to determine the competencies and training requirements for crews on ammonia-powered vessels, as they depend on resolving outstanding engineering and technical issues. The IMO and industry must work together to find solutions before finalizing training programs.

5 CONCLUSIONS

It is crucial to develop and implement policies that will drive investment within the necessary timeframes to meet the International Maritime Organization's (IMO) decarbonisation targets. The immediate focus should be on establishing policies that promote the adoption of fuels with zero climate impact on a lifecycle basis, considering both direct and indirect emissions. Green ammonia should be part of this fuel mix, with regulatory requirements ensuring its safety and environmental effectiveness.

However, the transition to ammonia as a marine fuel presents several challenges that must be addressed to realize its potential. Key issues include ensuring sustainable production from green sources, developing a global supply chain, and establishing rigorous safety regulations. The toxic and flammable nature of ammonia necessitates comprehensive safety protocols and extensive training for maritime personnel. Moreover, the current production capacity of green ammonia is insufficient to meet global shipping demands, requiring significant investments in infrastructure and technology.

The SWOT analysis highlights the strengths and opportunities that ammonia offers, such as its established global market and potential for technological advancements. It also outlines the weaknesses and threats, including high production costs, safety concerns, and the need for regulatory frameworks. Addressing these challenges will require coordinated efforts from stakeholders across the maritime industry, including shipbuilders, fuel producers, regulatory bodies, and policymakers. Continued research, innovation, and collaboration are essential to overcoming the barriers to its adoption, ensuring that ammonia can fulfil its potential as a keystone of clean maritime transport.

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