Ammonia as a Marine Fuel: Navigating the Tides of Decarbonization in the Maritime Industry

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Abstract:

The maritime industry is facing increasing pressure to decarbonize and reduce its reliance on fossil fuels. Ammonia, a carbon-free hydrogen carrier, has emerged as a promising alternative fuel for shipping. This review paper explores the potential of ammonia propulsion in ships, examining various technological approaches for its utilization, including internal combustion engines, fuel cells, and hybrid systems. It delves into the challenges associated with ammonia's adoption, such as toxicity, NOx emissions, infrastructure development, and regulatory frameworks. Finally, the future prospects of ammonia propulsion and highlight areas for further research and development is highlighted.

Keywords

Ammonia, Marine fuel, Maritime decarbonization, Green ammonia, Maritime emissions, Alternative fuels, IMO regulations, NOx emissions, Ammonia combustion, Shipping sustainability

1. Introduction

The global maritime industry operates over 90,000 vessels and facilitates approximately 80% of world trade by volume. Despite its efficiency in mass transportation, the sector remains a major emitter of carbon dioxide (CO_2), nitrous oxides (NO_x), and sulphur oxides (SO_x). The International Maritime Organization (IMO) has responded by adopting progressive GHG strategies that envision at least a 50% reduction in total annual GHG emissions from international shipping by 2050 compared to 2008 levels [1]. As part of these efforts, ammonia, a carbon-free fuel, has emerged as a promising alternative to traditional fossil fuels.

The maritime industry has traditionally relied on heavy fuel oil (HFO) and marine diesel oil (MDO) for propulsion. However, as international climate commitments tighten, the demand for cleaner fuels is increasing. Among these alternatives, ammonia has garnered significant attention due to its potential to be produced from renewable sources, such as wind or solar, and its carbon-free combustion properties [2], [5].

2. Ammonia as a Marine Fuel

Ammonia (NH_3) is an inorganic compound that has been used for over a century in agriculture and industry as a fertilizer and chemical feedstock. However, its potential as a marine fuel is now being explored. Ammonia can be synthesized from nitrogen and hydrogen via the Haber-Bosch process, and when burned as a fuel, it releases no carbon dioxide (CO_2), making it an attractive option for reducing maritime GHG emissions [6], [7].

Ammonia is already produced on a massive scale globally, with current production levels exceeding 180 million tonnes annually [8]. However, the vast majority of ammonia is produced using fossil fuels in a process that emits CO_2. To make ammonia a viable option for decarbonization, green ammonia, produced through electrolysis powered by renewable energy sources, must be prioritized [5], [9].

3. Chemical and Physical Properties of Ammonia

Ammonia is a nitrogen-hydrogen compound with the molecular formula NH3. It is colourless, with a pungent odour, and can be stored as a liquid under moderate pressure or at -33°C at atmospheric pressure. Key properties relevant to marine applications include:

Autoignition temperature: ~651°C

Boiling point: With a boiling point of -33 °C, it is a gas at room temperature and requires to be compressed and cryogenically stored.

Density: It has a density as a liquid fuel of approximately 0.68 g/cm³ at -33 °C. In its gaseous form at standard temperature and pressure, it is 0.77 Kg/m³

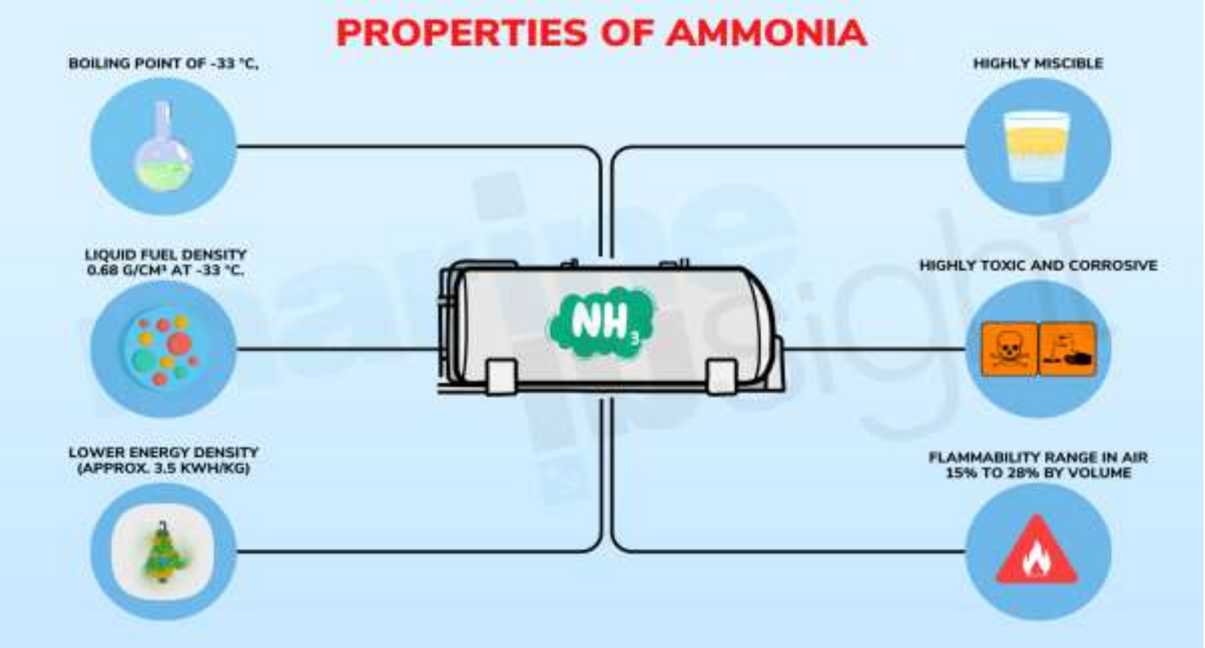
Solubility: Ammonia is highly miscible meaning it will readily dissolve in seawater in case of a spill. However, it is harmful to aquatic life and its effects vary depending on its concentration, the water temperature, and the pH levels.

Flammability: It is not inherently flammable but its flammability range in air is 15% to 28% by volume, meaning it can form explosive mixtures with air within this range.

Toxicity: It is highly toxic and Corrosive in nature and requires specialized handling.

Energy Density: Ammonia has a lower energy density (approx. 3.5 kWh/kg) compared to Heavy fuel oil (HFO) (approx. 12.6 kWh/kg). This means we need to burn almost three times as much quantity of Ammonia compared to HFO to achieve the same energy output.

Energy/Performance Efficiency: While energy density is lower, Ammonia offers near-complete combustion, leading to potentially improved engine efficiency compared to HFO. Factors such as Storage and Fuel economy will be key as ammonia-fueled ships will require more frequent bunkering depending on voyage lengths.



(Fig -1. www.marineinsight.com)

(https://www.marineinsight.com/green-shipping/introduction-to-ammonia-as-a-potential-marine-fuel/)

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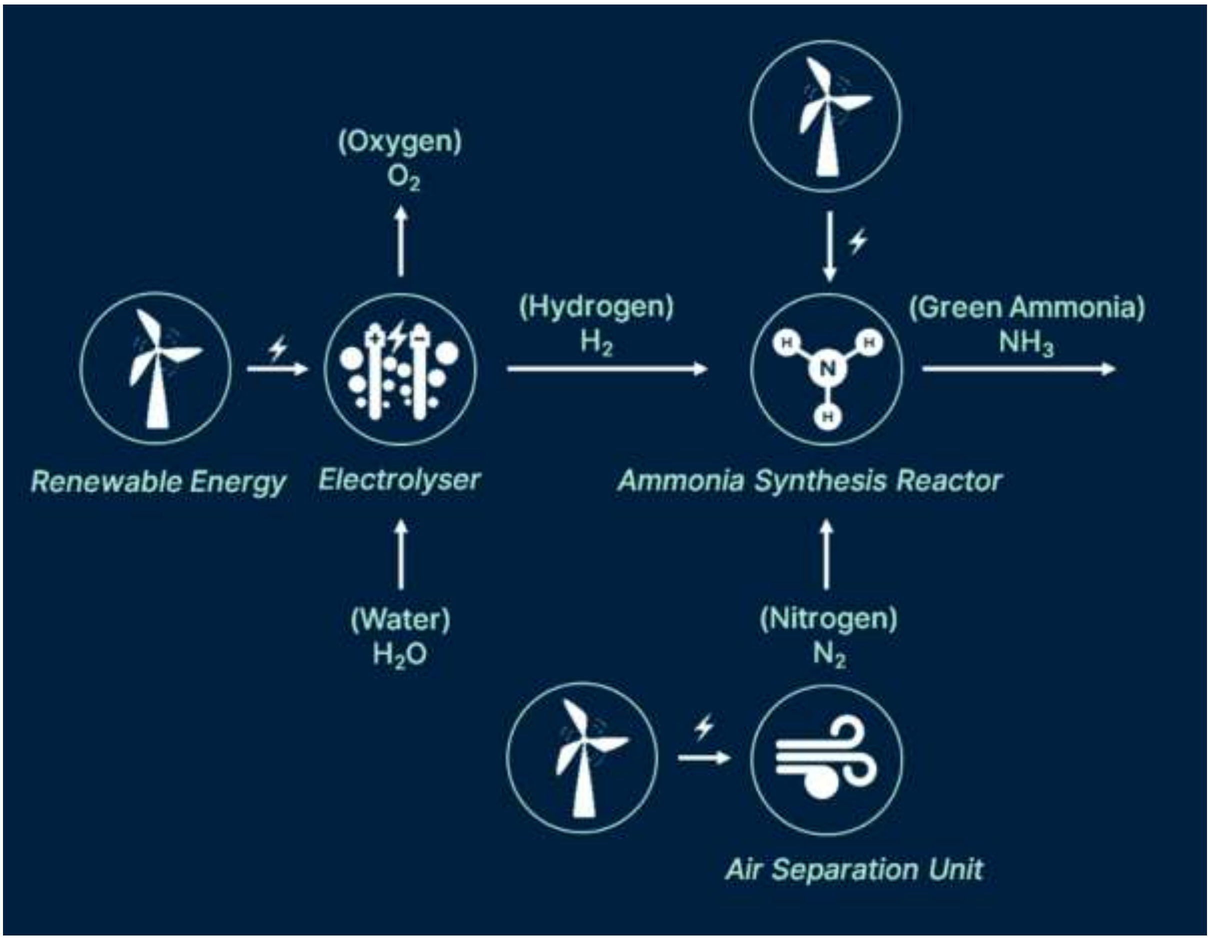
4. Types of Ammonia

The several types of Ammonia based on its production methods and use cases are:

Conventional Ammonia: Produced through the Haber-Bosch process, which combines nitrogen and hydrogen derived primarily from natural gas. This type of ammonia is typically used in fertilizers and industrial applications and can be adapted for use as a marine fuel.

Green Ammonia: Produced using renewable energy sources. The process involves generating hydrogen through the electrolysis of water using renewable electricity and then synthesizing ammonia from this hydrogen and atmospheric nitrogen. Green ammonia aims to minimize the carbon footprint associated with its production and is considered a more sustainable option.

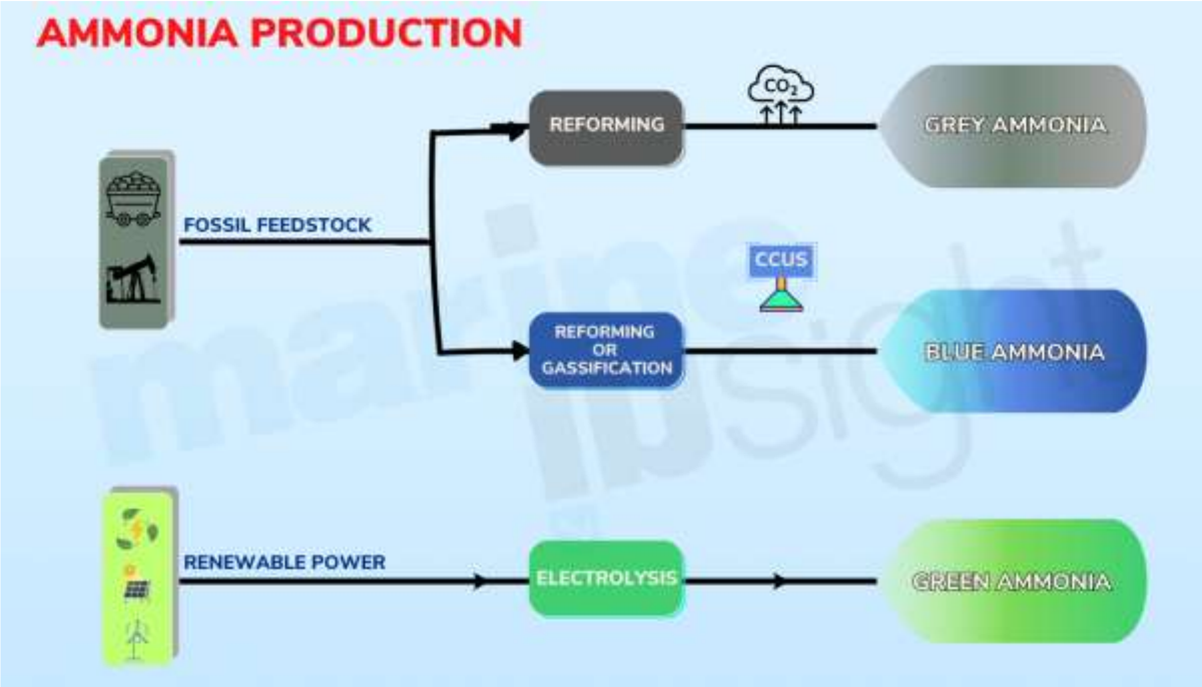


(Fig -2.)

(https://thrust.enviu.org/2020/03/19/7-reasons-why-ammonia-is-a-game-changer-for-the-maritime-industry/)

Blue Ammonia: Produced from natural gas, like conventional ammonia but with carbon capture and storage (CCS) technologies employed to reduce CO_2 emissions during production. Blue ammonia represents a transitional approach, aiming to lower the carbon intensity of ammonia production while transitioning to greener alternatives.

Grey Ammonia: Refers to ammonia produced from fossil fuels without carbon capture, leading to higher CO_2 emissions. It's the traditional form of ammonia and is less environmentally friendly compared to green and blue ammonia.



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5. Combustion Characteristics and Challenges

Ammonia combustion is more complex than traditional marine fuels due to its low flame speed, high ignition temperature, and tendency to produce nitrogen oxides (NO_x) [6], [10]. These challenges necessitate the development of specialized combustion technologies, such as ammonia-fueled engines and fuel cells, to optimize performance.

Despite the combustion challenges, ammonia's high energy density (approximately 18.6 MJ/L) is an advantage over hydrogen, which has lower volumetric energy density and requires cryogenic storage. Therefore, ammonia can potentially be stored and transported more efficiently [7], [8].

6. Ammonia a price competitive alternative to fossil fuels

Comparing the current costs for the production and use of (green) ammonia and low sulphur 0.5% HFO (Heavy Fuel Oil) today, the ammonia powered option is clearly more expensive. However, when considering near-future scenarios such as the expected decrease in the price of green ammonia based on lower electricity prices, the costs begin to close in on HFO prices rather quickly. When expected emission regulations like carbon taxation are added into the equation ammonia becomes price competitive. When comparing ammonia to other (non-fossil) alternative fuels it can be noted that its production requires less energy than carbon carriers like methanol, ethanol and LNG. The only alternative that can be produced with less energy is hydrogen, but storage of hydrogen requires far more energy – requiring either cooling to -253 degrees Celsius continuously, or high-pressure compression (350 to 700 bar). Ammonia only requires cooling to -34 degrees Celsius (liquid) or compression to around 10 bar at room temperature.

Fuel type	Energy density LHV [MJ/kg]	Volumetric energy density [GJ/m3]	Renewable synthetic production cost [MJ/MJ]	Storage pressure [bar]	Storage temperature [°C]
Marine Gas Oil (reference)	42.7	36.6	Not applicable	1	20
Liquid Methane	50.0	23.4	2.3	1	-162
Ethanol	26.7	21.1	3.6	1	20
Methanol	19.9	15.8	2.6	1	20
Liquid Ammonia	18.6	12.7	1.8	1 or 10	-34 or 20
Liquid Hydrogen	120.0	8.5	1.8	1	-253
Compressed Hydrogen	120.0	4.7	1.7	700	20

(Table -1.)

(https://thrust.enviu.org/2020/03/19/7-reasons-why-ammonia-is-a-game-changer-for-the-maritime-industry/)

7. Technological Developments in Ammonia-Based Marine Engines

Several manufacturers are developing ammonia-fueled marine engines. Wärtsilä, for example, is designing dual-fuel engines capable of running on ammonia, which would offer operational flexibility and reduce the risk of relying on a single fuel type.

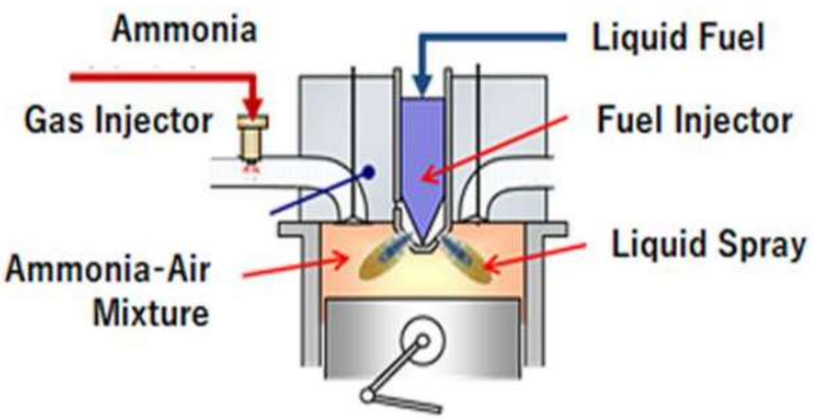
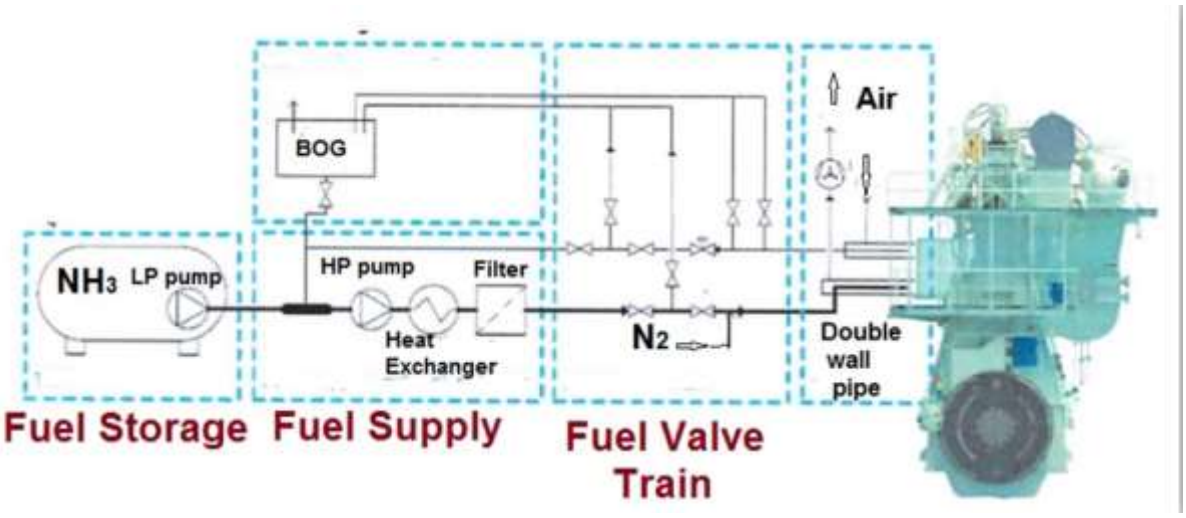


Fig.1 Ammonia mixed combustion in diesel engine

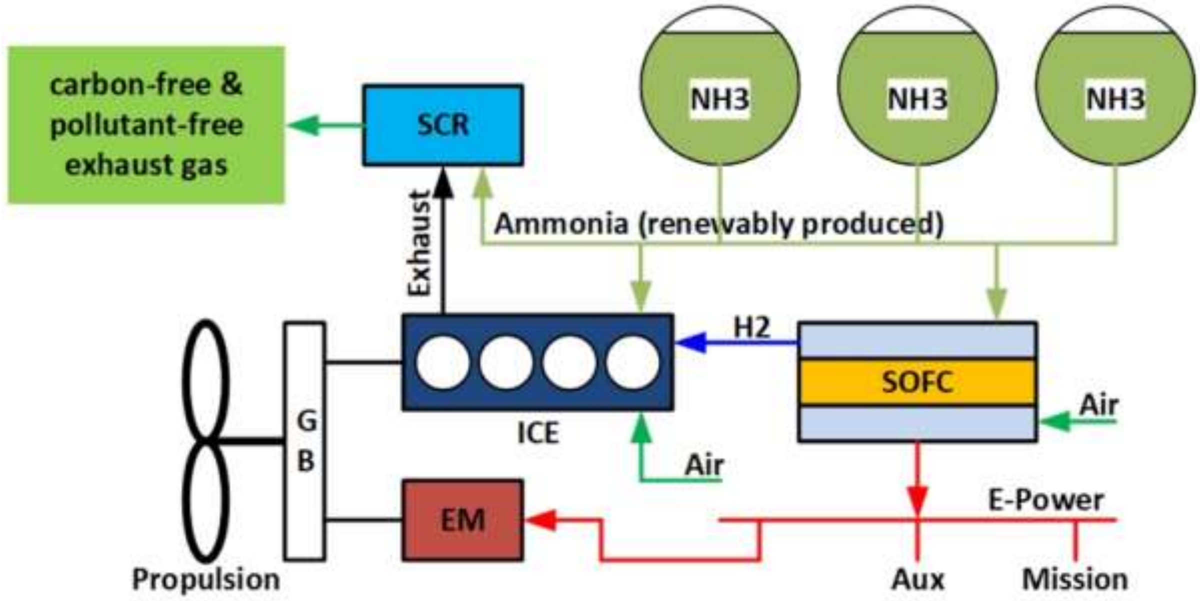
Similarly, MAN Energy Solutions is developing ammonia-based engines and has outlined plans for ammonia-powered vessels by the mid-2020s [9], [13].



(Fig -4.)

(https://www.mdpi.com/2071-1050/15/21/15565)

In addition to conventional internal combustion engines, ammonia fuel cells are being developed for marine applications. These fuel cells convert ammonia directly into electricity, with water and nitrogen as the only byproducts. Companies like AFC Energy are exploring ammonia-based fuel cells for marine use, which could complement or replace traditional combustion engines [14].



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(https://thrust.enviu.org/2020/03/19/7-reasons-why-ammonia-is-a-game-changer-for-the-maritime-industry/)

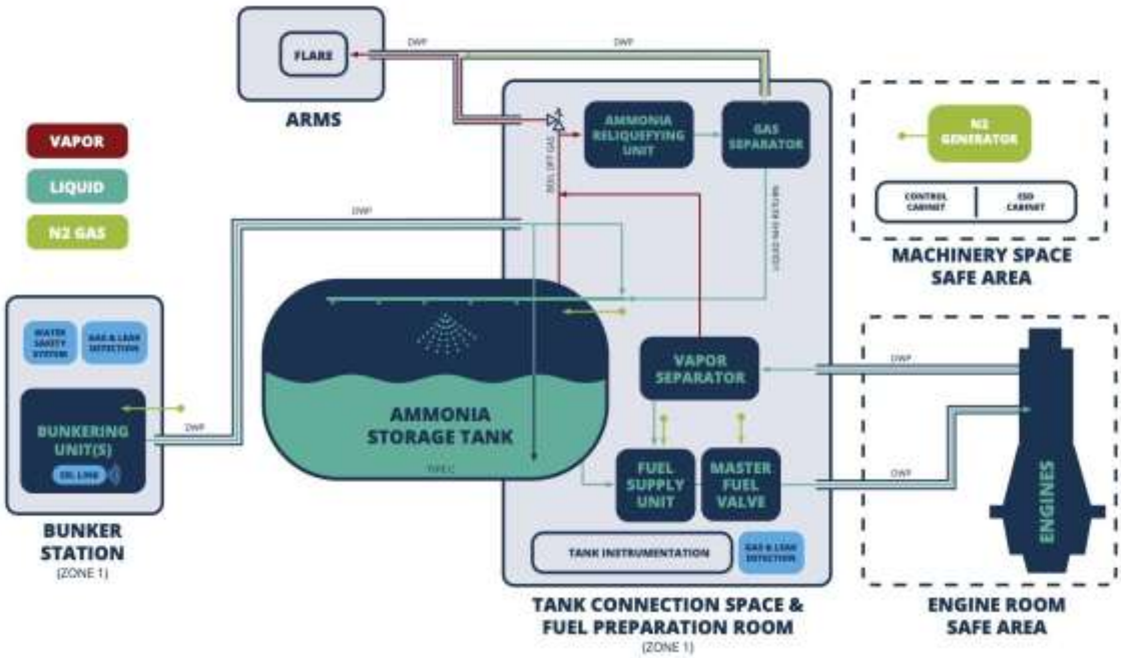
8. Ammonia Storage and Distribution in the Maritime Sector

Storage and bunkering of ammonia pose unique challenges. Ammonia must be stored at low temperatures or under pressure to remain in a liquid state, requiring specialized infrastructure [11]. Additionally, ammonia is toxic and poses significant health and safety risks, which has led to calls for the development of robust safety protocols for ammonia bunkering and handling [9].

To mitigate these risks, ammonia storage and bunkering systems must be designed with safety features such as leak detection, ventilation systems, and emergency shutdown capabilities.

Ammonia is a crucial chemical for the fertilizer industry and large quantities are produced every day around the world. Currently, this is mainly sourced from natural gas but due to the increasing prevalence of renewables in the global electricity sector, large scale sustainable ammonia production sites are expected to become feasible soon. Additionally, ammonia is already one of the most frequently transported chemicals worldwide and there are several vessels that have the infrastructure onboard to carry and handle ammonia across oceans, which means infrastructure for handling ammonia is already in place at all of the larger ports.

Furthermore, ammonia bunkering ports must be developed in strategic locations, and international regulations must be updated to accommodate ammonia fuel handling [11], [13].



(Fig -6.)

(https://www.auramarine/152937)

8.1. Procedures for the safe handling of ammonia

Ammonia is a flammable gas, but has a relatively low flammability risk in comparison to hydrogen and other fossil fuels, making it less explosive. The toxicity levels of ammonia, however, are far more severe than flammability levels making this the main element to focus on when it comes to safety and risks. Ammonia is a gas at atmospheric conditions and highly toxic. Ammonia can cause severe skin burns and eye damage and is lethal if inhaled. Furthermore, when dissolved in water ammonia is a serious threat to aquatic organisms, lethal at high concentrations. Therefore, strict detection systems must always be present when handling and storing ammonia. In addition, means to cope with leakages are required to reduce the concentration, an example being ventilation for enclosed spaces. Though these are serious considerations for ammonia as a fuel, it has been applied in other industries for many decades already. This means all the required protocols for the safe handling of ammonia already exist. It will rather be a matter of transferring these protocols towards maritime applications in order to safeguard the same safety levels. Particularly relevant for ship designs are the procedures to vent ammonia in case of any malfunction to avoid ammonia leaking into the ocean. [21]

9. Environmental Impact and Lifecycle Assessment

Ammonia is a zero-carbon fuel at the point of combustion, which makes it an attractive option for decarbonizing the maritime industry. However, the full environmental impact of ammonia as a marine fuel depends on the source of the ammonia itself. If ammonia is produced using renewable energy (green ammonia), its carbon footprint is minimal [5], [9]. Conversely, if ammonia is produced using natural gas (grey ammonia), the emissions associated with its production could undermine its environmental benefits.

The lifecycle analysis (LCA) of ammonia as a marine fuel must consider the entire supply chain, from production to transportation, storage, and combustion. Green ammonia, when produced from renewable sources, offers a promising pathway toward decarbonizing the maritime industry and reducing global shipping emissions [5], [10].

10. Regulatory Landscape and Policy Mechanisms

The IMO plays a pivotal role in shaping the regulatory framework for alternative fuels. Its 2023 Revised GHG Strategy sets a vision of net-zero emissions from international shipping by 2050, and ammonia is identified as a key fuel for achieving these targets. Regulatory mechanisms such as the Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), and the Fuel EU Maritime Initiative are pushing the adoption of low-emission fuels, including ammonia [1], [3].

Countries such as Japan and Norway are actively supporting the development of ammonia-based propulsion systems, with national funding and regulatory support driving the adoption of ammonia as a marine fuel. Furthermore, financial mechanisms such as carbon pricing and emission trading schemes (e.g., EU ETS) will provide incentives for early adopters of ammonia [8], [13].

In India the government aims to have a port supplying green fuels in 2025 and two vessels retrofitted to run on H2 or derivatives in 2027. India's Ministry of New and Renewable Energy has unveiled details of its programme in February 2024 to support pilot projects for green hydrogen in shipping. The country targets at least one port with green ammonia bunkering and refuelling facilities in 2025, as well as two ships retrofitted by the state-owned Shipping Corporation of India to run on green H_2 or its derivatives in 2027.IRCLASS has published the guidelines on Ammonia fueled vessels in December 2022. [22]

11. Case Studies and Demonstration Projects

Several pilot projects are underway to test the feasibility of ammonia as a marine fuel. The Castor Initiative, a collaboration between Lloyd's Register, Samsung Heavy Industries, and MAN Energy Solutions, is developing an ammonia-powered Aframax tanker, which is expected to enter service by 2026 [15].

Additionally, Amogy's ammonia-powered tugboat, launched in 2023, represents a significant milestone in ammonia propulsion technology [14].

The Amogy owned NH_3 Kraken, a tugboat originally constructed in 1957 and retrofitted with Amogy's ammonia-to-electrical power system, sailed on a tributary of the Hudson River, upstream from New York City.

Amogy's patented ammonia-to-electrical power system splits, or "cracks," liquid ammonia into its base elements of hydrogen and nitrogen. The hydrogen is then funnelled into a fuel cell, generating high-performance power with zero carbon emissions. This technology offers a sustainable, clean energy solution, tailored for hard-to-abate sectors like maritime shipping, as well as stationary power generation applications. During the demonstration, the NH_3 Kraken was fueled with green ammonia, produced entirely with renewable energy, further reducing its carbon footprint.

(Fig -7.)

(https://amogy.co/news/moving-the-maritime-industry-closer-to-clean-energy-amogy-is-building-the-worlds-first-ammonia-powered-zero-emission-ship)

Norwegian ammonia distributor Yara Clean Ammonia and Japan's shipping company NYK Line have concluded in February 2025 what is said to be the "world's first" time-charter contract for an ammonia-fueled medium gas carrier. The vessel, to be delivered in November 2026, will fly the Japanese flag with a 40,000 cubic meter capacity and an overall length of 180 meters. [12]

An ammonia-fueled ammonia bunkering vessel design developed for use in Singapore has received approval in principle (AiP) from classification society ClassNK. The 'pioneering' vessel design was delivered by Japanese shipping major NYK Line in collaboration with LMG Marin, a wholly-owned subsidiary of Seatrium, and other consortium partners. The vessel's design are being submitted to the Maritime and Port Authority of Singapore (MPA) for evaluation.

The AiP certification validates the ammonia-fueled ammonia bunkering vessel design's compliance with stringent safety, technical, and environmental standards.

LMG Marin conducted a Hazard Identification Study (HAZID) to ensure design validation and compliance with the International Maritime Organization's (IMO's) interim guidelines for the safety of ships using ammonia as fuel.

The vessel design also incorporates the consortium's two key features to ensure safety and operational reliability: ammonia fuel dual-fuel engines from IHI Power Systems and a bunkering boom by TB Global Technologies.

The engines, which are said to significantly reduce greenhouse gas (GHG) emissions using ammonia as a fuel, are also installed on the world's first commercial-use ammonia-fueled tugboat, Sakigake, delivered in August 2024. The bunkering boom features a unique technology called the High-Speed Ammonia Purging Emergency Release System (ERS), which is expected to enable a reliable and efficient disconnection between vessels in an emergency.[12]

(Fig -8.)

(https://www.offshore-energy.biz/worlds-first-commercial-use-ammonia-fueled-tugboat-achieves-95-emission-reduction/)

NYK Tugboat Sakigake, the world's first commercial-use ammonia-fueled vessel, reached a greenhouse gas (GHG) emission reduction of up to approximately 95%.

The emission reduction was recorded during the three-month demonstration voyage which commenced after the tugboat was converted from LNG- to an ammonia-fueled vessel in August 2024.

The conversion project was completed by NYK and IHI Power Systems (IPS) in cooperation with ClassNK as part of a Green Innovation Fund Project under Japan's New Energy and Industrial Technology Development Organization (NEDO).

During the demonstration period, Sakigake performed tugboat operations in Tokyo Bay. NYK and IPS analysed the ammonia co-firing and GHG reduction rates during vessel operations and confirmed them to consistently exceed 90% and rise to approximately 95% in each of the main engine load ranges.[12]

These projects are critical for understanding the technical, safety, and operational challenges of ammonia-powered vessels. The outcomes of these projects will inform future ship designs, engine technologies, and fuel supply chain infrastructures [15].

12. Strategic Analysis (SWOT Analysis)

Strengths:

- Carbon-free combustion
- High energy density compared to hydrogen

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- Existing global ammonia production infrastructure
- Compatibility with renewable energy

Weaknesses:

- Toxicity and safety concerns
- High ignition temperature and low flame speed
- High production costs for green ammonia
- Limited existing ammonia bunkering infrastructure

Opportunities:

- Regulatory support and financial incentives
- Technological advancements in ammonia engines and fuel cells
- Growth of green ammonia markets
- Export potential for ammonia-rich countries

Threats:

- Competition from other alternative fuels (e.g., biofuels, LNG)
- Public perception and environmental risks
- Uncertainty in global standardization
- High capital investment for infrastructure

(Fig -9.)

(https://thrust.enviu.org/2020/03/19/7-reasons-why-ammonia-is-a-game-changer-for-the-maritime-industry/)

13. Lifecycle Emissions Analysis

A comparative lifecycle analysis of various marine fuels shows that ammonia produced from renewable sources has a significantly lower carbon footprint than conventional fuels such as HFO and LNG. Green ammonia produced via electrolysis offers near-zero well-to-wake (WtW) emissions, making it one of the most sustainable fuel options for maritime decarbonization [5], [9].

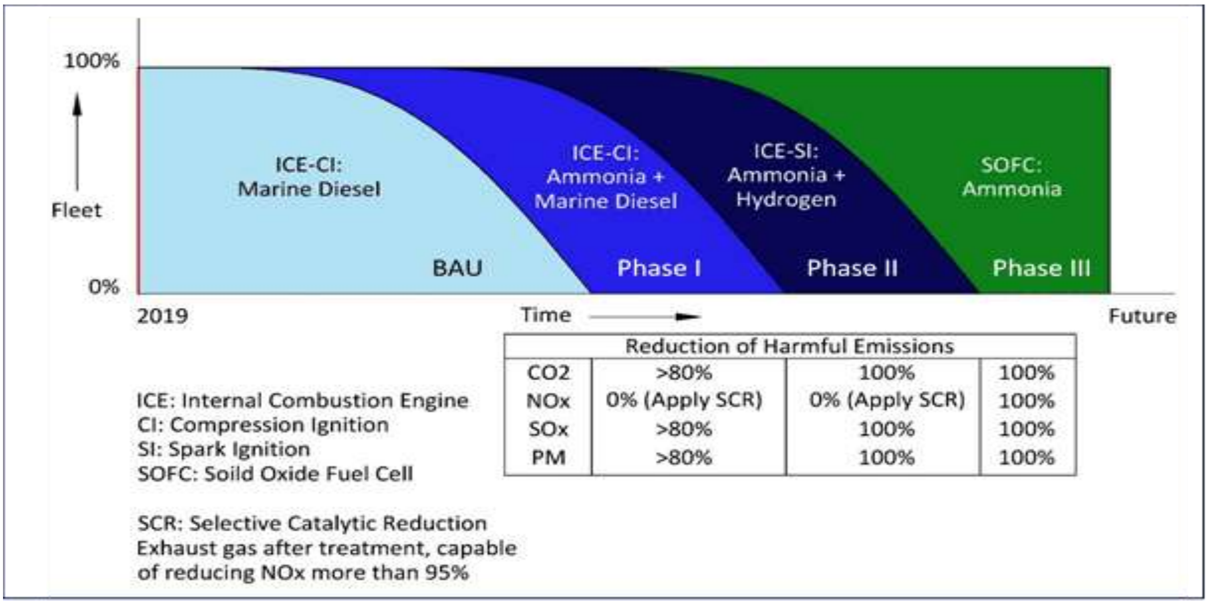
14. Ammonia as an Excellent Transition Fuel

The important advantage of ammonia is that it can be applied relatively easily in a dual-fuel combination into existing on-board internal combustion engines, significantly reducing harmful emission whilst generating the same amounts of energy with the same efficiency as fossil fuels. In its pure form ammonia combustion does have several challenges such as a high auto-ignition temperature and narrow flammability limits. To improve the overall combustion properties of ammonia, its application in mixtures makes sense. The ideal zero-emission mixture would be ammonia with a small percentage of hydrogen to improve combustion, where hydrogen is cracked (extracted) from ammonia. This is currently a relatively complicated set-up, because it means implementing two new fuels into the operations of existing vessels. In the short term, blending ammonia with diesel makes more business sense as it requires only limited modifications to existing engines, with particular attention to the manufacturing materials, because ammonia is corrosive for zinc, copper and other alloys. The National Maritime Research Institute of Japan has done extensive research in this field, with very promising results at a representative scale.

However, despite being much cleaner than fossil fuels this solution will never be 100% harmful emission free as it will require Nox removing. Therefore, this solution acts as a first step to accelerate the introduction of ammonia as a fuel in the maritime industry before making the next step towards truly 100% zero emission shipping via the use of fuel cells. [21]

15. The Ammonia Roadmap

In the medium to long term and when SOFC technology is developed with related price level drops, the operational business case for green ammonia in combination with SOFC will become an increasingly attractive one and a great solution truly free from harmful emissions. An example of what the overall transition pathway may resemble like is visualized in the graph below.



Reduction of Harmful Emissions			
CO2	>80%	100%	100%
NOx	0% (Apply SCR)	0% (Apply SCR)	100%
SOx	>80%	100%	100%
PM	>80%	100%	100%

(Fig -10.)

(https://thrust.enviu.org/2020/03/19/7-reasons-why-ammonia-is-a-game-changer-for-the-maritime-industry/)

In phase I, ammonia will be used in combination with diesel in an ICE, resulting in a significant reduction in harmful emissions. This allows the operator to select the amount of ammonia himself offering flexibility to cope with the ever changing economic viability and complying with harmful emission reduction regulations. Furthermore, this will allow for a backup solution and the capability to switch back to 100% diesel in case operations fail while implementing this solution. This way continued operations can be guaranteed. In phase II, diesel can be replaced with hydrogen, leading up to the SOFC replacing the ICE in Phase III, eliminating Nox emissions altogether and leading to a truly zero emission solution.

16. Future Outlook and Research Agenda

The future of ammonia as a marine fuel is promising, but several technical and economic barriers must be addressed. Continued investment in ammonia combustion technologies, fuel cells, and safety systems is crucial. Additionally, regulatory clarity and international cooperation will be key to scaling ammonia adoption across global shipping routes.

Research efforts should focus on optimizing ammonia engines, improving fuel production processes, and enhancing ammonia storage and bunkering infrastructure. Furthermore, international standardization of ammonia bunkering procedures and fuel specifications will facilitate the global integration of ammonia into the maritime fuel mix [13], [14].

17. Conclusion

Ammonia presents a viable and sustainable pathway for decarbonizing the maritime industry. Its carbon-free combustion, scalability, and compatibility with renewable energy sources make it a promising candidate for meeting the IMO's decarbonization goals by 2050. However, overcoming the challenges of toxicity, combustion efficiency, and fuel infrastructure will require continued innovation, collaboration, and investment.

By addressing these challenges, ammonia has the potential to play a central role in the maritime industry's transition to a sustainable, net-zero future.

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