The UUPO project – New fuels for maritime logistics as drivers of green transition and blue growth

Fuel Info Package: Ammonia

samk

Satakunta University of Applied Sciences

SATAKUNTALIITTO

Regional Council of Satakunta

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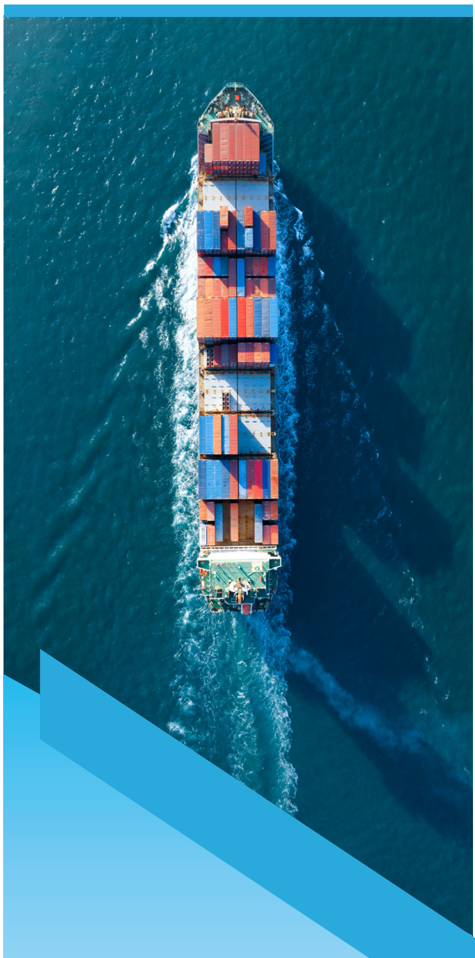
Basic information



Important notes:

1. The use of ammonia does not produce any carbon dioxide, but incomplete combustion in engines can lead to the production of nitrous oxide, a significantly more potent greenhouse gas

2. Ammonia is not yet in use in maritime transport

3. Ammonia is highly toxic to humans, organisms, and ecosystems, making its use challenging

4. Ammonia can be used as a fuel in various ways

5. Ammonia produces significantly fewer SOx and particulate matter emissions compared to traditional fuels

Ammonia

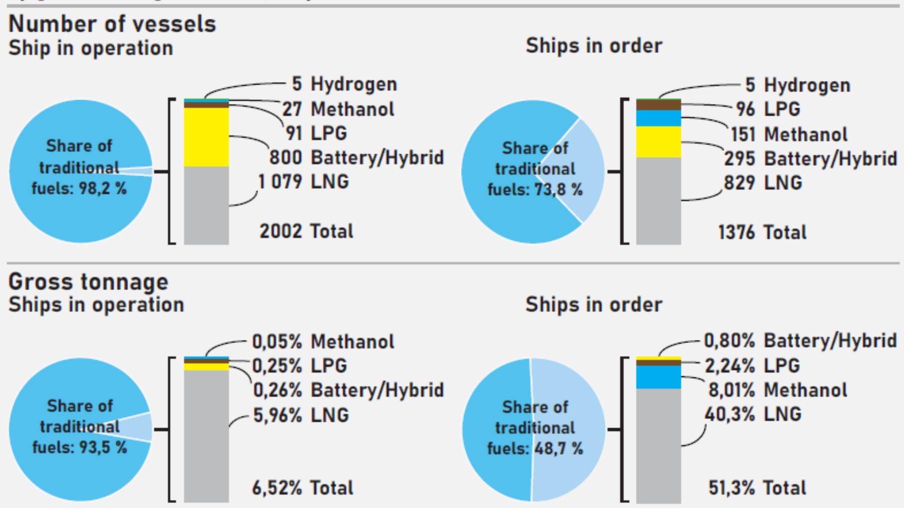
Ammonia (NH_3) is a carbon-free compound consisting of one nitrogen atom and three hydrogen atoms. At normal temperature and pressure, ammonia is a colorless, toxic, and corrosive gas with a pungent odor.

Ammonia has been produced on an industrial scale for over a hundred years, a period during which significant advancements have been made in production technology and practices. [1] Today, ammonia is a crucial component in various industries, with approximately 80% of global ammonia production being used in the manufacturing of fertilizers. [2]

Thanks to its carbon-free nature, burning ammonia does not produce any carbon dioxide, and under optimal conditions, the combustion reaction only results in nitrogen and water. This makes it a potential replacement for traditional fuels in maritime transport. Although there is increasing interest in ammonia as a fuel and significant development work has been done, ammonia-powered vessels have not yet appeared on the seas. Its adoption has been hindered by challenges such as ammonia's toxicity, availability, and the lack of fuel distribution infrastructure in maritime settings. [3]

However, various ammonia trials have been conducted on different types of vessels, and the world's first ammonia-powered container ship is expected to be operational in Norway by 2026. [4] This significant milestone demonstrates that technological and logistical challenges are gradually being overcome, and ammonia may become a viable and important alternative fuel in maritime transport.

Figure 1. Adoption of alternative fuels in the global fleet by the number of vessels (top) and by gross tonnage (bottom), July 2023



Citations: [1], [2], [3], [4], [Figure 1]

Production methods

Nearly all ammonia is produced using the Haber–Bosch process. In this method, hydrogen and nitrogen are fed into a reactor where they react in the presence of an iron-based catalyst under high pressure and temperature, forming ammonia. In addition to the Haber–Bosch process, ammonia can also be produced using other methods, such as the electrolysis process, also known as electrochemical synthesis. [5] Like many other new fuels, ammonia is classified into different “colors” depending on how the hydrogen used in the process is produced. [6]

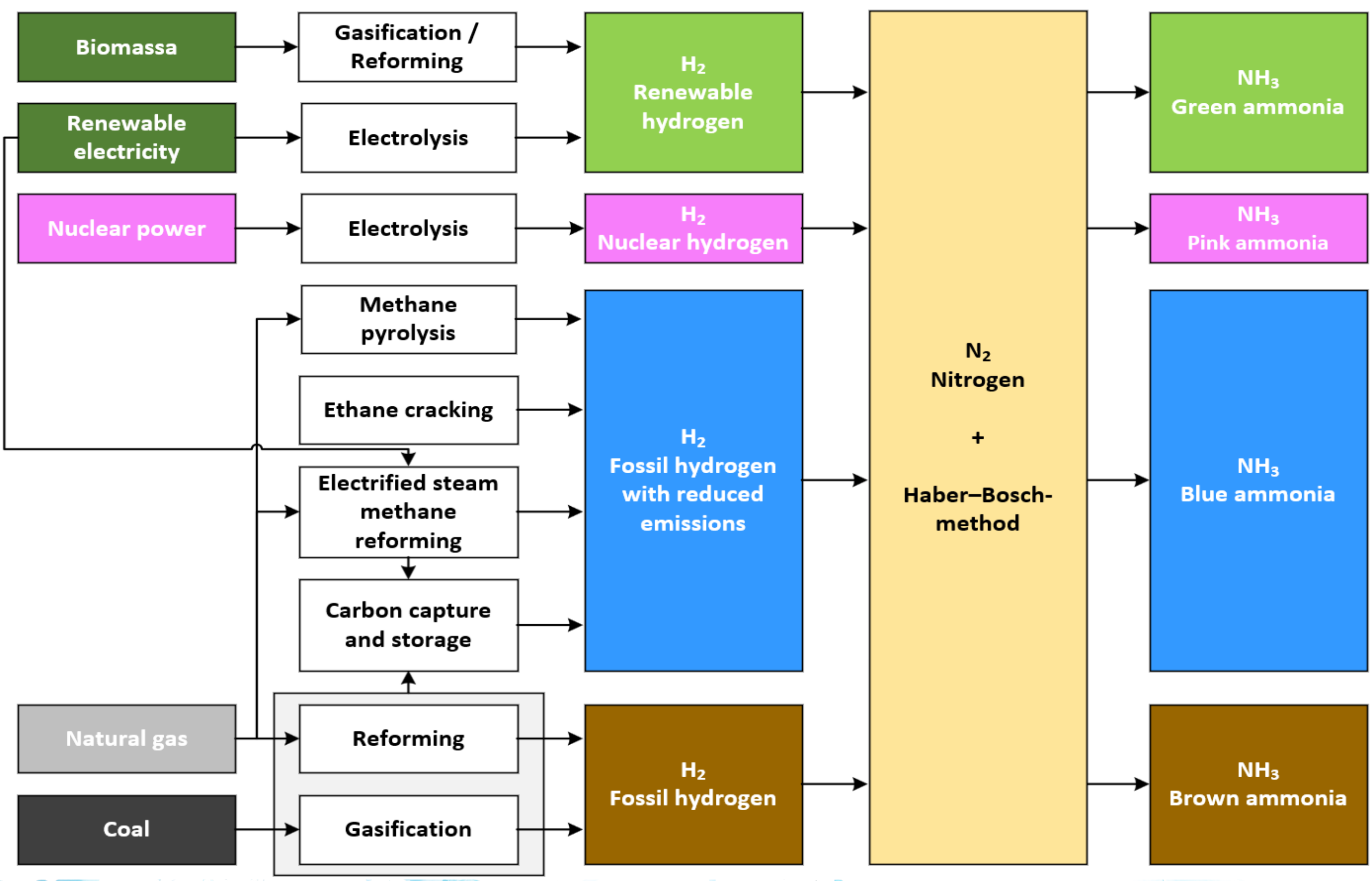
Brown ammonia

In brown ammonia production, the hydrogen used is derived from fossil fuels, leading to high lifecycle emissions. The amount of emissions depends on the specific fossil fuel used. For example, the production of black ammonia, where the hydrogen comes from coal, produces nearly twice as much lifecycle emissions as grey ammonia, in which hydrogen is derived from natural gas. Over 90% of ammonia production currently relies on fossil fuels. [7]

Blue ammonia

Blue ammonia is primarily produced through processes similar to those used for brown ammonia, but most of the greenhouse gas emissions are prevented from entering the atmosphere using various technological solutions. One example is carbon capture, where the emissions are captured and stored in geological formations. Captured carbon dioxide can also be used in processes such as the production of synthetic fuels. [8] Additionally, the hydrogen for blue ammonia can be produced through processes

Figure 2. The main methods for producing ammonia



Citations: [5], [6], [7], [Figure 2]

Production methods

that generate fewer greenhouse gas emissions, such as methane pyrolysis. Hydrogen produced by this method is sometimes referred to as turquoise hydrogen. [9]

Green ammonia

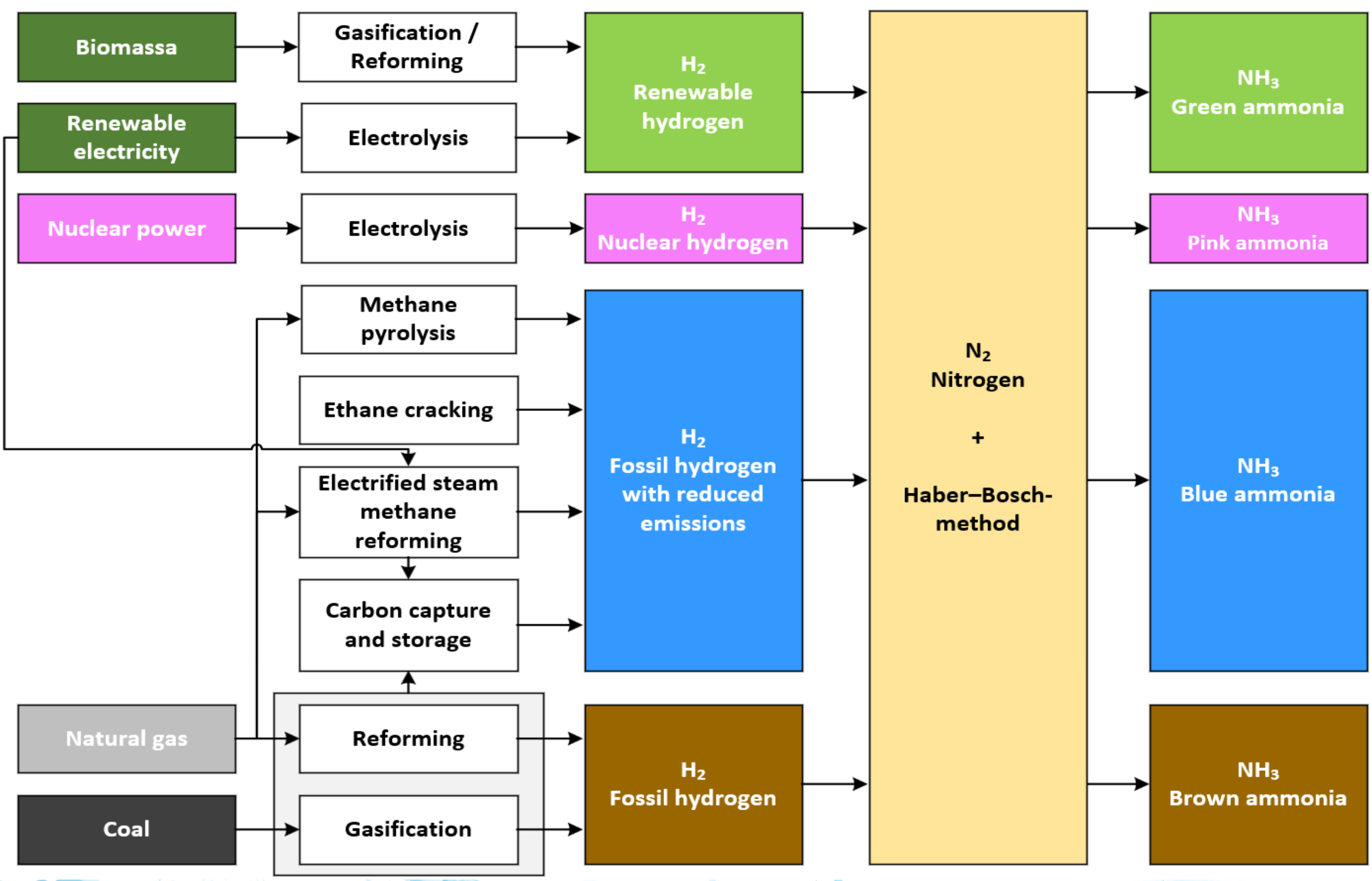
In green or renewable ammonia, the hydrogen is produced by methods that generate little to no greenhouse gas emissions. The most common ways to produce green hydrogen are through electrolysis and biomass gasification and reforming. [10] In electrolysis, hydrogen is produced by using renewable electricity to split water into hydrogen and oxygen. The challenges with this process include the amount of energy required for electrolysis and the availability of fresh water. These challenges can significantly impact the cost and scalability of green ammonia, especially in areas where renewable energy resources are limited and fresh water is scarce. [11]

Hydrogen produced from biomass, on the other hand, is generated by gasifying biomass, where it is heated to high temperatures, resulting in the production of synthesis gas. This synthesis gas can be processed to produce hydrogen as the end product. [12]

Pink ammonia

Pink ammonia is produced using hydrogen generated through electrolysis, similar to green ammonia. However, the key difference between the two lies in the energy source used to power the electrolysis process. While green ammonia relies on renewable energy sources, pink ammonia is produced using electricity derived from nuclear power. [13]

Figure 2. The main methods for producing ammonia



Citations: [8], [9], [10], [11], [12], [13], [Figure 2]

Properties and safety aspects

Fuel properties

Compared to traditional fossil fuels, liquefied ammonia (L NH_3) has a relatively low heating value. When comparing the energy densities of fuels, the difference between ammonia and traditional fuels becomes even more pronounced due to ammonia's low density. As a result, ammonia requires approximately three times the storage space to store the same amount of energy as heavy fuel oil.

Ammonia also has poor ignition properties, which make its use as a fuel challenging. Its extremely high autoignition temperature necessitates that the temperatures and pressures within the combustion chambers of engines reach elevated levels, which can place additional stress on the engine and its components. For this reason, ammonia in combustion engines is sometimes used with a pilot fuel that has a lower autoignition temperature to initiate the combustion process. In practice, this means that the pilot fuel ignites first due to the rising temperature and pressure in the combustion chamber, and the energy released by the pilot fuel then ignites the ammonia. The type of pilot fuel and its share of the total fuel mix depends on the engine type. [14]

In addition, ammonia has a low flame propagation speed and a relatively narrow flammability range, making its use as a fuel even more difficult. [15]

Safety aspects

Ammonia gas is lighter than air, which causes it to rise and accumulate near the ceiling in enclosed spaces. However, it reacts readily with moisture in the air, which may cause the density of the ammonia gas to increase beyond that of air. As a result, it can settle close to the ground as a white gas. Typically, in the event of an ammonia leak, water is sprayed into the air to bind the ammonia and prevent it from spreading further from the leak site. [16]

For humans, ammonia is extremely toxic, and even small concentrations can cause symptoms of exposure. Ammonia can also cause chemical burns to various parts of the body by reacting with bodily fluids. However, these injuries can be prevented if the person who comes into contact with ammonia is quickly moved to a washing area or emergency shower. [17]

	Energy and storage					Flammability		
Fuel	Density [kg/m^3]	Lower heating value [MJ/kg]	Energy density [MJ/m^3]	Boiling point [°C]	Fuel volume requirement vs. LSHFO	Autoignition temperature in air [°C]	Flashpoint [°C]	Flammability limits in air [%]
LSHFO	993	40,5	40 217	> 180	-	230	> 60	0,6 - 7,5
MDO	819	40,5	33 170	> 180	1,21	210	> 60	0,6 - 7,5
LNG	450	49,1	22 095	-162	1,82	540	-188	5,0 - 15,0
MeOH	792	19,9	15 761	65	2,55	464	12	6,7 - 36,0
EtOH	789	26,8	21 145	78	1,90	365	17	3,3 - 19,0
L NH_3	**680**	**18,6**	**12 648**	**-33**	**3,18**	**651**	**132**	**15,0 - 28,0**
L H_2	70	120	8 400	-253	4,79	585	-	4,0 - 75,0
FAME	880	37,2	32 736	> 180	1,23	261	> 61	0,6 - 7,5
HVO	780	44	34 320	> 180	1,17	204	> 61	0,6 - 7,5
FT-Diesel	785	43,2	33 912	> 180	1,19	204	89	0,6 - 7,5

Citations: [14], [15], [16], [17], [Table]

Production

Global production

Ammonia is the second most produced chemical in the world by mass, after sulfuric acid, with an estimated production of around 183 Mt in 2020. That year, the global production capacity was approximately 243 Mt. [18]

The production of ammonia results in about 0,5 Gt of carbon dioxide emissions, accounting for nearly one percent of all annual emissions. This level of emissions is partially explained by the fact that only 0,02 Mt of the ammonia produced in 2021 was renewable ammonia. However, the share of green ammonia is expected to grow rapidly, with reported annual production capacity for renewable ammonia plants projected to reach 15 Mt by 2030 based on current estimates. [19]

As ammonia use expands across various applications, its production and demand are expected to grow rapidly. Global production is projected to rise to approximately 700 million tons by 2050. [20] Some estimates suggest this figure could be closer to 900 million tons. [21]

A potential future solution may involve producing ammonia at the location where it is used, aligning with the principles of decentralized electricity generation. This would mean, for example, that ammonia could be produced at a small facility, such as on a farm or a ship, where it would ultimately be used for various applications. Research on this concept has been conducted at Monash University in Melbourne, Australia. [22]

Future outlooks in Finland and Satakunta

Although large quantities of ammonia are produced globally, there are currently no production facilities in Finland. However, this situation may change, as in May 2023, YLE reported that the American company Plug Power is planning to build three green hydrogen production facilities in Finland, located in Kokkola, Kristiinankaupunki, and Porvoo. The Kokkola facility would also produce ammonia for fuel and as an energy source for the process industry. However, these projects are still in the planning phase, with a final investment decision expected to be made between 2025 and 2026. [23]

Additionally, Satakunnan Kansa Länsi-Suomi reported in March 2024 on a study by Prizztech and Rejlers, in which these companies planned to build an ammonia plant in Rauma. The investment value is estimated to be around 720 million euros, and this type of production facility would produce approximately 240 000 tons of ammonia annually. The produced ammonia could be utilized in local industries, such as the fertilizer plant in Uusikaupunki and the nickel refining plant in Harjavalta. Furthermore, the ammonia could be easily transported by tank trucks from the production facility to the port of Rauma, where it could be used for maritime transport. [24] In addition to Rauma, Green North Energy is also exploring the possibility of constructing a green ammonia plant in Pori, with an annual production capacity of approximately 210 000 tons. [25][26]

Citations: [18], [19], [20], [21], [22], [23], [24], [25], [26]

Technical aspects

Infrastructure

Ammonia is currently produced in large quantities for the fertilizer industry, which means that there are existing transportation methods and built infrastructure. However, in terms of maritime logistics, bunkering opportunities are crucial when considering the broader adoption of this new fuel. In this regard, infrastructure projects for ammonia are already under development. In October 2023, Yara and Azane Fuel Solutions announced their collaboration to construct the first bunkering unit, demonstrating concrete progress in developing this infrastructure. [27] Ammonia cannot be used as is within the current fuel infrastructure, which means that its broader use in shipping will require significant investments in infrastructure.

Transportation

The technology for storing, transporting, and distributing ammonia is already highly developed. Additionally, the expertise, practices, training, regulations, and standards are established, which will facilitate its adoption in maritime applications. [28]

Ammonia can be transported in smaller quantities and over shorter distances using tank trucks, pipelines, and trains. However, the majority of transported ammonia is shipped by sea. Currently, approximately 20 Mt of the produced ammonia is transported by sea each year using 170 different vessels. [29] These ships transport ammonia in liquid form, similar to liquefied gas, which may also allow for the future repurposing of liquefied gas transport vessels for ammonia transport. These types of vessels can carry about 30,000–80,000 m^3, or approximately 20–55 kilotons of ammonia. [30]

Storage

Ammonia can be stored as a liquid or gas. Storing ammonia in liquid form is typically the better option as it takes up less space, making it a more efficient and convenient choice for storing and transporting large quantities. Ammonia has a boiling point of -33 °C, which means its storage in liquid form is significantly easier than that of LNG or hydrogen, whose boiling points are -162 °C and -252 °C, respectively. Liquid storage requires cryogenic tanks that continuously cool the ammonia to ensure the temperature does not exceed the boiling point. These cryogenic tanks typically occupy more space than traditional fuel tanks. Since the boiling point of liquefied gas (-42 °C) is slightly lower than that of ammonia, a liquefied gas cryogenic tank can also be used for ammonia storage. [31]

In tanks and other materials that come into contact with ammonia, its corrosiveness must be considered. Ammonia can cause corrosion in various steels and other metals, particularly in the presence of moisture. Oxygen dissolved in liquid ammonia can exacerbate corrosion in pipelines and tanks used for transporting and storing ammonia. Furthermore, ammonia can react with nitrogen and sulfur oxides in the air, forming various compounds such as ammonium sulfate and ammonium nitrate. These compounds can also react with different materials, increasing the risk of corrosion. Due to the safety risks associated with ammonia storage and handling, great care must be taken to minimize these risks and hazards. [32]

The storage of ammonia on ships is regulated by the IMO's IGC Code. The placement of fuel tanks must be designed to minimize risks of tank damage. For example, tanks must be located a sufficient distance from the engine room and other high fire-risk areas, as well as from locations where various mechanical damages, such as those resulting from crane accidents, could occur. [33]

Citations: [27], [28], [29], [30], [31], [32], [33]

Technical aspects

Use as fuel

Ammonia is a versatile fuel that can be utilized in various ways. It can be used in internal combustion engines similarly to traditional fuels. Ammonia can also be used in fuel cells, which generate electricity through a chemical reaction without the traditional combustion process. Additionally, ammonia can be cracked, or broken down into its constituent parts, resulting in a mixture of hydrogen and nitrogen. This process allows for the utilization of hydrogen in hydrogen-powered internal combustion engines or fuel cells.

Ammonia has made significant strides in its use as a maritime fuel in recent years. For example, the American company Amogy has successfully demonstrated the functionality of ammonia in various vehicles, including tractors and trucks. They have also initiated a collaboration with SEAM to retrofit an ammonia system on a tugboat. Amogy's ammonia fuel systems are based on the cracking of ammonia. [34] The cracking of ammonia into hydrogen has garnered interest from various other companies, and its role in the future of shipping is still yet to be determined. One of the advantages of ammonia cracking into hydrogen is that ammonia is significantly easier to store than hydrogen. [35]

Research has also been conducted on ammonia-powered fuel cells. For instance, a study published in 2023 presented a design concept for a 2200–2800 TEU container ship powered by a solid oxide fuel cell. The researchers noted that ammonia and fuel cells could effectively serve as a power source for this type of vessel, although the technology still requires optimization in several areas. [36]

In addition to ammonia fuel cells and cracking, ammonia internal combustion engines have gained popularity recently. For example, automotive manufacturers GAC Group and Toyota collaborated to release a prototype utilizing an ammonia engine in passenger cars in 2023. [37] In the maritime industry, engine manufacturer MAN Energy Solutions reported a successful laboratory test of their two-stroke ammonia engine in the fall of 2023. Their goal is to bring this type of engine into commercial use by 2026. [38]

Additionally, Wärtsilä announced its development of the world's first commercially available four-stroke ammonia engine in the fall of 2023. According to the announcement, the company aims to finalize commercial agreements for the engine by early 2024. [39] In April 2024, it was reported that Wärtsilä would deliver its first ammonia engine in early 2025. [40]

Other maritime engine manufacturers, such as Hyundai Heavy Industries, STX Engine, Winterthur Gas & Diesel, and IHI Power Systems, are also researching and developing ammonia engines, with plans to bring these to market within a few years. [41]

These projects, prototypes, and research initiatives demonstrate the viability of ammonia in various solutions and accelerate its use as a maritime fuel. Estimates suggest that the share of ammonia in the maritime fuel market could be around 20–60% by 2050, depending on various scenarios. [42]

Citations: [34], [35], [36], [37], [38], [39], [40], [41], [42]

Environmental aspects

Ammonia plays a significant role in the green transition of marine logistics, as it offers a sustainable alternative to traditional fuels. Ammonia can be produced using renewable energy sources such as solar and wind power, which reduces reliance on fossil fuels or raw materials and thereby lowers emissions from shipping. Additionally, the logistical chain and storage of ammonia are already established infrastructures, facilitating its integration into a greener shipping sector. Therefore, ammonia appears to be a promising alternative for a sustainable future in marine logistics, but its drawbacks must also be understood and taken into account.

Greenhouse gas emissions

As mentioned earlier, ammonia does not contain carbon, so its use does not produce any carbon dioxide or other carbon-based greenhouse gases. However, in ammonia internal combustion engines, nitrous oxide (N2O) is produced due to incomplete combustion, which is over two hundred times more potent as a greenhouse gas compared to carbon dioxide. Some studies have shown that increased nitrous oxide in the atmosphere may negate the carbon-free benefits of ammonia, leading to accelerated climate change compared to fossil fuels. [43] However, this topic requires further research to better understand the actual effects of nitrous oxide produced from ammonia.

It is also crucial to consider how ammonia is produced concerning greenhouse gas emissions, as gray or brown ammonia has significantly higher life-cycle emissions than green ammonia.

Nitrogen oxides emissions

Ammonia itself contains nitrogen, so its use as a fuel produces significant NOx emissions. Additionally, the amount of emissions can be affected if the combustion of ammonia in the internal combustion engine is incomplete. NOx emissions may also occur if unburned ammonia is present in the exhaust gases, as ammonia reacts in the atmosphere to produce various nitrogen oxides, such as nitrous oxide. [44]

Sulfur oxides emissions

Ammonia does not contain sulfur, so the sulfur oxide emissions it produces are practically nonexistent. However, small amounts of SOx emissions can occur due to impurities present in the fuel. Besides impurities, sulfur oxide emissions may also arise from the pilot fuel if such fuel is used. Due to low SOx emissions, ammonia is an excellent fuel option for sulfur oxide emission control areas. [45]

Other emissons

The use of ammonia as a fuel produces very low amounts of particulate emissions compared to traditional fuels. The amount of particulates may increase if a pilot fuel is used in conjunction with ammonia. [46] Other emissions may also include ammonia emissions caused by unburned fuel.

Fuel spills

Large ammonia leaks can be extremely destructive to ecosystems. On land, ammonia consumes water from plant leaves, while in water bodies, ammonia can kill sensitive fish and aquatic species and cause eutrophication and pH changes. [47][48]

Citations: [43], [44], [45], [46], [47], [48]

Summary

Ammonia is not yet used in shipping and is seen as a future fuel like hydrogen, as its use still involves significant challenges. One of the biggest challenges is safety, as ammonia is highly toxic and can be dangerous to both people and the environment in the event of leaks. Improving safety measures and training personnel handling ammonia will play a crucial role in its future adoption in shipping. The effective use of ammonia as a fuel also requires the development of technology and infrastructure to ensure its handling, storage, and combustion are carried out as safely and efficiently as possible.

However, ammonia has significant advantages compared to many other alternative fuels. For instance, ammonia contains no carbon, meaning its use does not produce carbon dioxide emissions. Incomplete combustion can, however, produce nitrous oxide emissions, which is a much more potent greenhouse gas.

It is also important to note that although ammonia can be produced using renewable energy sources, most of the current ammonia is produced from fossil raw materials, which significantly impacts its life-cycle emissions.

If the challenges related to the use of ammonia can be addressed, it could become one of the most important fuels in shipping. This would help reduce greenhouse gas emissions and promote more sustainable maritime transport.

Strengths

+ Ammonia is one of the few carbon-free fuels and can be produced using renewable energy sources, so it has the potential to significantly reduce greenhouse gas emissions in shipping

+ Ammonia produces virtually no SOx or particulate matter emissions.

+ Ammonia is currently produced in large quantities, so there is existing infrastructure for its production and distribution.

+ Liquid ammonia is easier to store than LNG or liquid hydrogen due to its relatively higher boiling point.

+ Ammonia has been produced for a long time, providing a wealth of experience and knowledge regarding its manufacturing processes.

Weaknesses

- Ammonia is not yet used in shipping, so the standards and practices related to its use are still in development.

- Ammonia is highly toxic, making its use challenging.

- It may require pilot fuels to operate in combustion engines.

- Currently, most ammonia is produced using fossil raw materials.

- The energy density of ammonia is significantly lower than that of fossil fuels.

- The fertilizer industry uses a lot of ammonia, which may affect the availability of ammonia

- Incomplete combustion produces various emissions, such as nitrous oxide

- Ammonia contains nitrogen, so its combustion results in significant nitrogen oxide emissions

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