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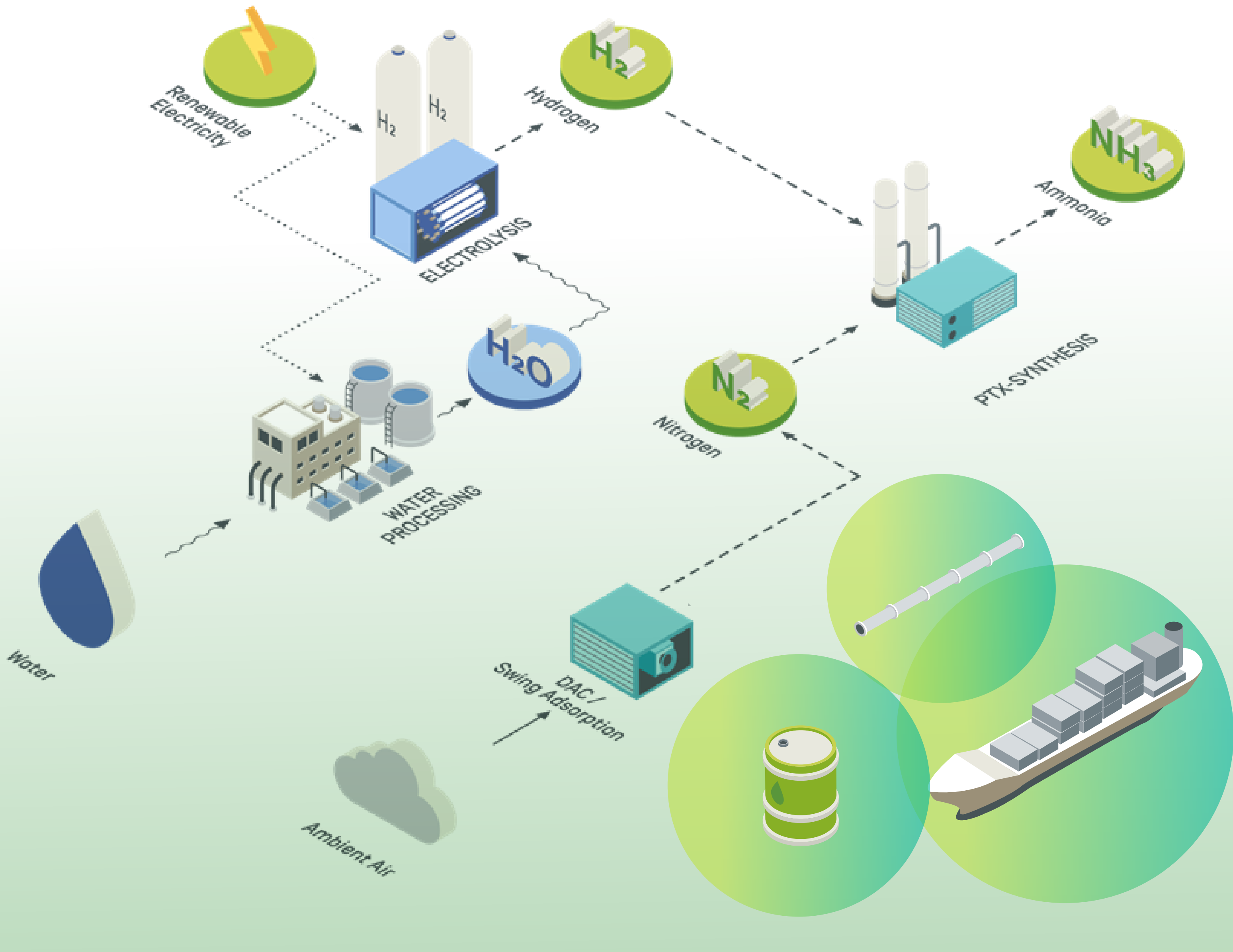
AMMONIA TRANSPORT & STORAGE

#2



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OVERVIEW

Paper #2 delves into the key aspects of ammonia storage and transportation and highlights various methodologies and technologies that play a central role in the ammonia supply chain. The first chapter deals with the storage of ammonia as a crucial element for its utilisation as an energy source and chemical feedstock. It examines various pressure storage methods, including semi-refrigerated storage, low-temperature storage, and solid-state storage. A detailed comparison of these ammonia storage alternatives sheds light on their respective advantages and limitations.

Efficient transportation is fundamental in facilitating the widespread use of ammonia. The second chapter looks at the different modes of ammonia transport, ranging from traditional methods such as pipeline transportation to ocean and barge transport, rail and truck transport. It critically analyses and compares these transport alternatives, considering factors such as safety, cost-effectiveness, and environmental impact.

Through a comprehensive exploration of pressure storage and transportation methods, this paper aims to provide a thorough understanding of the technological landscape surrounding ammonia logistics. By offering insights into storage options and transportation modes, the paper contributes to the development and optimisation of ammonia supply chain systems, fostering a more sustainable and efficient utilisation of this versatile chemical compound.

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ABBREVIATIONS

API	American Petroleum Institute
Br	Bromine
Ca	Calcium
Cl	Chlorine
e.g.	exempli gratia
etc.	et cetera
GHG	Greenhouse gas
H_2	Hydrogen
Li	Lithium
LPG	Liquefied Petroleum Gas
MAPCO	Mid-America Pipeline Company LLC
Mg	Magnesium
NH_3	Ammonia
SCC	Stress corrosion cracking
TRL	Technology Readiness Level

UNITS

$	Dollar
°C	Degree Celsius
barg	Bar gauge
cm	Centimetre
g	Gram
kg	Kilogram
km	Kilometre
L	Litre
m	Metre
m^3	Cubic metre
mbar	Millibars
mm	Millimetre
psig	Pounds-force per square inch gauge
t	Tonnes
wt%	Weight percent

INTRODUCTION

Ammonia is a chemical molecule with many uses, such as fertiliser in agriculture, coolant or medium for storing energy. Its adaptability and the ability to store and transport hydrogen, a pure and effective energy carrier, are the key to its potential. Ammonia can be produced using a number of renewable energy-based techniques. One of these is electrolysis, where renewable electricity is used to split water into hydrogen and oxygen. Ammonia is then produced by combining hydrogen and nitrogen. Given its toxicity and reactivity, the safe and effective transport and storage of ammonia are essential components of its use. This paper looks at the various strategies and factors involved in the storage and transport of ammonia.

The containers used to store ammonia range from tiny containers to huge tanks. These containers can be either spherical or cylindrical, depending on the storage capacity and safety requirements. For capacities of up to 150 tonnes of ammonia, cylindrical, usually horizontal tanks are used. For larger capacities, spherical tanks are used, which can have a capacity of 250 to 1,500 tonnes and are often supported by pillars or shallow depressions to increase stability. Maintaining the integrity of these tanks is of paramount importance. Materials such as high-strength or fine-grained steels are used, but these can be susceptible to stress corrosion cracking from ammonia. Controlling the water content in the ammonia plays a role in reducing this corrosion.

Temperature control is important in addition to corrosion. Ammonia is kept chilled in fully refrigerated tanks, where it can be kept at a temperature of -33 °C. Ammonia is kept at lower pressures and about 0 °C in semi-refrigerated storage by employing less complex refrigeration systems. While operating at ambient temperatures and pressures, atmospheric ammonia storage tanks require careful consideration of the materials to prevent stress corrosion cracking.

Ammonia is transported through a variety of means, including pipelines, rail, trucks, ocean and barge transport, and ships. Long-distance pipeline transmission is cost-effective, but temperature management is necessary to prevent brittle fracture. Ammonia is transported by rail and truck in pressurised liquid form. Insulated vessels with refrigeration systems are used for ocean and barge shipment. The choice will depend on elements including distance, accessibility, and volume, as well as the infrastructure and economic concerns that apply to each mode. Additionally, rules governing water content requirements for corrosion protection apply to the transportation of ammonia.

Solid-state ammonia storage techniques have attracted attention recently due to their increased safety and reduced volatility. At room temperature, substances like metal halides can absorb ammonia, opening up a potentially useful storage option.

This paper underscores the diversity and complexity of ammonia storage and transportation methods, reflecting the critical role ammonia plays in various industries and the need for safe, efficient, and economically viable solutions. One of the advantages of ammonia is that it has an important infrastructure for storage, transportation, and handling [1]. In addition, there have been mature storage facilities and technologies for ammonia for 100 years.

Production plants always require facilities for ammonia storage. It is common practice to have storage capacity of at least 15 days of production even if all of the ammonia is used at the plant site where it is produced [2]. This storage serves as a buffer capacity to compensate for fluctuations in production and demand between the ammonia plant and the downstream units and, in the case of plants that export ammonia, also to store the product between shipments [3]. Storage near loading and unloading points is also necessary to balance fluctuations in the ammonia market [4].

The largest ammonia storage facilities are located at distribution centres, in terminals, or in ammonia production sites. A large number of smaller storage tanks are usually operated by ammonia distributors and are used for distribution and local storage [5].

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Ammonia is usually handled in liquid form, but in some cases delivery of ammonia vapour to downstream consumers on site may have some advantage due to savings of refrigeration energy in the ammonia plant [6]. It is important to note that storage of gaseous ammonia would require larger tanks to store the same amount of ammonia as liquid storage as the density of ammonia gas is lower than that of the liquid. For instance, liquid ammonia expands to 850 times its liquid volume at atmospheric pressure [7].

Currently, the main methods for storing ammonia are [8]:

- Pressure storage at ambient temperature in spherical or cylindrical pressure vessels with capacities up to 1,500 tonnes per vessel.
- Semi-refrigerated storage at about 0 °C in insulated, usually spherical pressure vessels for quantities up to about 2,500 tonnes.
- Atmospheric storage at -33 °C in insulated cylindrical tanks for around 50,000 tonnes each tank.
- Solid-state storage

The first three forms of storage are mature technologies widely used throughout the world and even combinations of these methods can be found in practice [4]. However, the solid-state storage is still under development. The first chapter describes these forms of storage.

It shall be clarified that another method for large-scale ammonia storage is cavern/underground storage, which is a common practice in the Liquefied Petroleum Gas (LPG) industry. Two rock caverns storing ammonia facilities are reported to be operated by Dupont (United States) and Norsk Hydro (Norway) with capacities of 20,000 and 50,000 tonnes, respectively. However, due to the problems associated with contamination of the liquid ammonia and the lack of suitable geological sites, such storage facilities are not normally considered feasible and have not been built for a long time [6]. They are therefore not discussed in this section.

1

PRESSURE STORAGE

Pressure vessels store liquid ammonia at ambient temperature in containers that are similar to the low-pressure vessels used for LPG [9]. The pressurised storage tanks are found in sizes down to one to a few kg capacities and as large as 1,500 tonnes [5].

The containers could be cylindrical or spherical depending mainly on the desired storage capacity. The cylindrical ones, usually horizontal are used for up to 150 tonnes. Spherical containers, which rest on tangentially arranged support columns, but also more recently for static and safety reasons in a suitably shaped shallow depression, are used to storage 250-1,500 tonnes [6]. Typically, cylindrical pressure vessels are designed for about 25 bar and the larger spherical vessels only for about 16 bar to avoid wall thicknesses above 30 mm. In hot weather, non-refrigerated pressurised storage containers are usually protected from overheating by an outer insulation, a reflective coat of paint, water spray, or the circulation of ammonia through a water cooler [3].

This system is especially suitable for

- storing small quantities of ammonia as intermediate storage between the ammonia plant and clients,
- balancing production variations with downstream units processing pressurised ammonia,
- loading and unloading trucks, tank cars, and marine vessels carrying pressurised ammonia,
- entrance to or exit from pipeline systems,
- and in the distribution system for storage of small quantities of ammonia, for example in field tanks in connection with direct application of liquid ammonia as a fertiliser [3].

Ancillary equipment for these vessels includes meters and flow controls for pressurised ammonia feed and effluent streams, centrifugal pumps for discharging into liquid ammonia supply piping and for liquid ammonia loading, pressure safety valves, equipment for safe pressure relief for ammonia vapour and inerts [6].

The metallurgy of the steel used for storage, tanks, transport vessels, and pipelines is extremely important. Sometimes high-strength or fine-grained steels are used as materials for pressure vessels manufacturing. These may be susceptible to stress corrosion cracking by ammonia, which is a highly discussed problem in pressurised storage tanks. Despite extensive research, the mechanism of this phenomenon, the influence of water and the role of oxygen are not yet fully understood [6].

However, it is generally recognised that a water content in ammonia reduces stress corrosion cracking. It has therefore become common practice to maintain a water content of at least 0.2 % in transport containers made of certain types of steel. Additional protection can be achieved by cathodic polarisation, e.g. by aluminium or zinc metal spray coating [3].

It should be noted that each type of steel has a transition temperature below which they are prone to brittle fracture. The brittle fracture is initiated at a notch or crack, usually near a weld where a stress occurs, and once initiated, it may spread quickly. Thus, a vessel or pipeline should not be operated below its transition temperature unless it has been thermally stress relieved after fabrication. This special treatment is expensive and sometimes impractical. For this reason, pressure vessels and pipelines should not be filled with refrigerated ammonia. The ammonia should be heated to a temperature above the transition temperature of the steel used in the vessel [2].

1.1 Semi-refrigerated storage

Semi-refrigerated systems allow the storage of refrigerated liquid ammonia at low pressure in an insulated container. The ammonia is kept at a moderately low temperature around 0 °C at which the gauge pressure is only 3-4 bar. This allows the use of much lighter steel tanks than if the temperature were uncontrolled [128]. Semi-refrigerated storage vessels are normally spheres and may have capacities up to about 3,000 tonnes [3].

The refrigeration system of these vessels is simple: the ammonia vapour from the container is compressed in a single stage compressor and liquefied by water cooling, and the liquid is returned to the tank. Therefore, the system is similar in principle to fully refrigerated storage, but much less sophisticated and relatively inexpensive [2].

Semi-refrigerated ammonia tank and refrigeration system

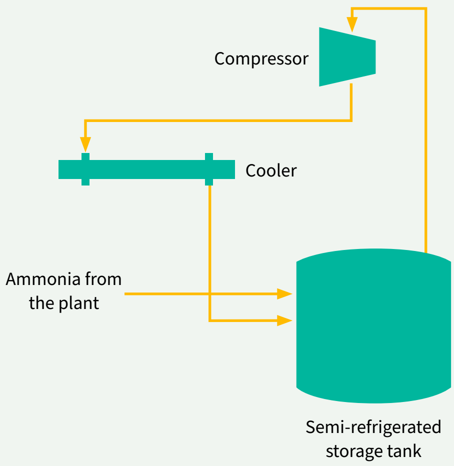

Figure 1: Own illustration

1.2 Low-temperature storage

Liquid ammonia, especially at large quantities, is stored in fully refrigerated tanks, also known as atmospheric ammonia storage tanks. These containments are cylindrical, insulated tanks with flat bottom and domed roof, operate slightly above atmospheric pressure and -33 °C and with capacities up to 50,000 tonnes [2] [9]. This shows that one of the advantages of ammonia is that it is easier to store than liquid hydrogen, as the latter is stored cryogenically at a much lower temperature, namely -253 °C [10].

The refrigeration in this kind of tanks is provided by a refrigeration unit, normally with a two-stage ammonia compressor. The refrigeration may also be integrated with the ammonia synthesis loop refrigeration system [3]. The temperature is kept down by slow vaporisation, and the ammonia vapour is continually compressed back to a liquid [11].

If warm liquid ammonia under pressure is received from the ammonia plant synthesis loop, it is brought to near atmospheric pressure before entering the tank. During this process, part of the ammonia evaporates, causing the temperature to drop to -33 °C. Due to evaporative cooling of ammonia, the liquid ammonia is fed into the storage tank at this temperature and the vapours are handled by the refrigeration compressor [3].

The first stage of compression handles the ammonia gas coming out of the storage tank. The vapour is compressed from less than 1 psig up to 2 to 4 bar and then cooled in the flash tank in preparation for the second stage of compression, which increase vapour pressure from 2 to 4 bar up to condensing pressure of 10 to 16 bar. The following step is the ammonia condensation, in which condensed ammonia is sent to a receiver. The receiver level control directs the liquid to the flash tank and the flash tank level control directs the liquid to the storage tank [12]. Figure 2 shows a simple diagram of the refrigeration system.

Atmospheric ammonia tank and refrigeration system

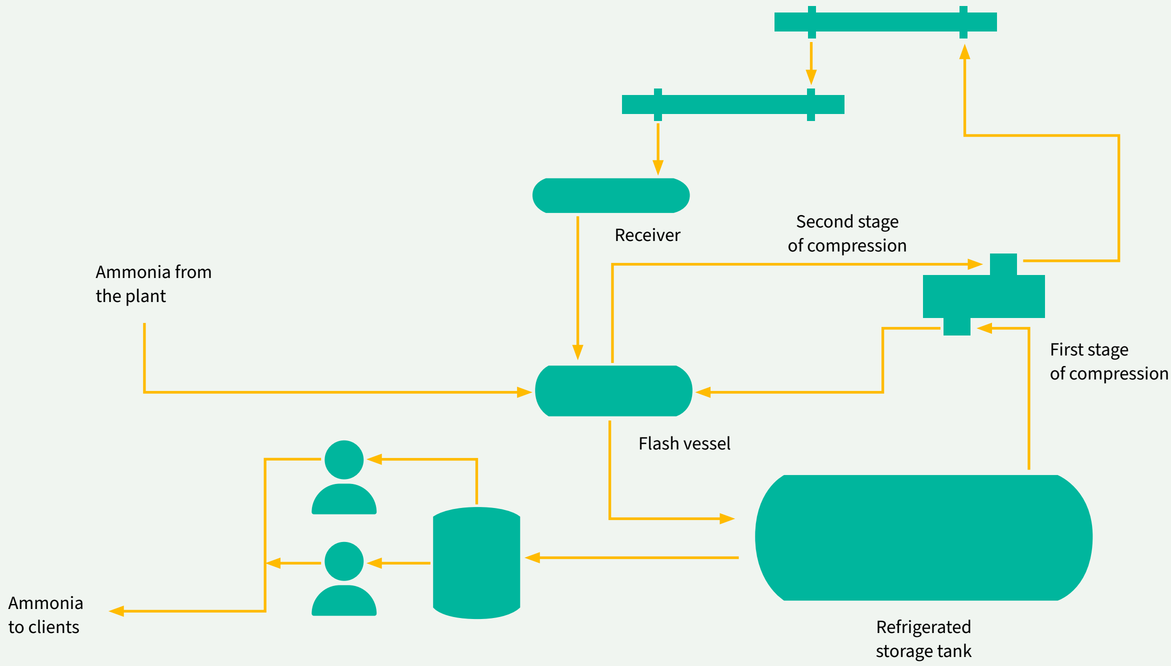

Figure 2: Own illustration

Ammonia received from the ammonia plant contains small gas impurities from the synthesis plant, such as nitrogen, hydrogen and argon. These gases do not condense and must be purged from the second-stage compressor. When the storage tank is not filled, a relatively small amount of ammonia evaporates due to the heat that is conducted into the tank through the insulation. This heat causes ammonia to vaporise in a relatively small amount, which is handled by a small compressor. When the tank is being filled, a larger quantity of ammonia vapour is formed, requiring the use of a larger compressor [2].

There are two types of refrigerated ammonia storage tanks: single and double wall [4]. The former consists of a single shell insulated on the outside to avoid freezing moisture [3]. The insulation must be completely vapour-tight, and a very high standard of construction and maintenance is required to avoid hazards. Normally mats or panels of rock wool, foam glass, styrofoam, polyisocyanurate foam, or polyurethane foam, and an aluminum jacket are used as isolation [4].
The double wall tanks consist of an inner tank designed for the storage temperature and pressure surrounded by a second tank, with a gap between the two shells of normally 18 inches or more. In a conventional double wall tank, the annular space between the walls is filled with insulation materials such as loose-fill perlite, while dry gas (air, nitrogen, or inert gas) is filled in the interstitial space to protect the insulation.

It is becoming increasingly common practice to design the outer shell to the same standards as the inner shell ('double-integrity' tanks) so in case the inner tank fails, the outer tank can contain the ammonia [3]. If this is not the case, a containment bund around the atmospheric tanks with a 100% capacity of the largest tank plus 10% capacity of all other tanks inside the same bund is recommended.

The tanks can be placed either directly on the ground or on piles. In the first case, heating of the ground is required to avoid freezing. This could lead to movements damaging the bottom and the foundation of the tanks. The use of concrete platforms with ventilation under the bottom eliminates the requirement of heating [4].

Although the investment cost for the double-wall tank is greater than for single-wall construction, maintenance costs are usually lower [2].

Ammonia stress corrosion cracking is also a risk on atmospheric tanks, although for a long time it was believed to be a problem only of non-refrigerated and semi-refrigerated tanks operating at higher pressures and temperatures [6] [3]. The low-temperature tank base is usually constructed according to standards (such as API 625) and using carbon-manganese steel certified to limit the effect of stress corrosion cracking (SCC) [4].

1.3 Solid-state storage

There is a growing trend towards the use of pressurised storage which is in line with the trend towards small-scale ammonia plants. However, a significant disadvantange of conventional storage methods is high ammonia vapour pressure of 7 to 8 bar at ambient temperature, [8] which, in addition to its toxicity, raises safety concerns when storing liquid ammonia for end-user applications.

Therefore, the use of a solid material as ammonia storage has become the promising method to utilise ammonia for practical applications [13]. This increases the safety of the system, as ammonia can only be desorbed when heated or depressurised, which prevent leakage.
Many kinds of complex materials have been considered to store ammonia at moderate temperature and pressure and without a cooling system, such as amide/imide systems, halides, complex metal hydrides, metal fullerides and borohydrides [11]. However, these materials require improvements of the properties for development as practical materials [13].

Among the materials currently under investigation, metal halides stand out [14]. Metal halides MXm (where M is a metal cation such as Mg, Ca, Li, etc. and X is an halide such as Cl, Br) absorb ammonia at room temperature, forming metal ammines (M(NH3) nXm), which are solid salts [15]. The reaction is as follows [16]:

$$\underset{\text{(metal halide)}}{MX_m} + nNH_3 \leftrightarrow \underset{\text{(metal ammine)}}{M(NH_3)_n X_m}$$

The absorption/desorption of ammonia is completely reversible. As a result of the much lower ammonia volatility and release rate at room temperature compared to liquid ammonia, the material is approved for on-road and air transport [17].

Additionally, these metal ammines can be shaped into highly compact bodies, essentially without any void space. Thus, the metal ammine gives a gravimetric hydrogen content of about 9 wt.% and an energy density of 105 to 110 kg H_2/m^3 (similar to that of liquid ammonia, 108 kg H_2/m^3) [17]. This can be seen in Figure 3.

Mass and volume of 10 kg of hydrogen stored reversibly by different methods

Figure 3: Based on [11]

So far, the best studied metal ammine salt is $Mg(NH_3)_6Cl_2$ due to the low vapour pressure of 2 mbar at room temperature and the high gravimetric (9.19 wt.%) and volumetric (109 g H_2/L) hydrogen density. However, there have been recently intensive research on $Ca(NH_3)_8Cl_8$ since its hydrogen density is as high as 9.78 wt.% and the release of ammonia is achieved at lower temperatures than with $Mg(NH_3)_6Cl_2$, thereby reducing the energy needed to desorb the ammonia. The disadvantage is that this salt is less stable and has a higher ammonia vapour pressure at room temperature (0.7 bar, which is still an order of magnitude lower than that of liquid ammonia) [11].

The most practical configuration of this storage alternative is having a storage with many cylinders of about 0.5 to 1.0 diameter and a few meters in height. After desorption at 350 °C, the cylinders are cooled with nitrogen flow from the pressure swing absorption unit [8].

Despite the extraordinary capacity of metal halides for ammonia storage, achieving equilibrium capacity is difficult. The absorption capacity normally accomplished is 1 to 5% of the equilibrium capacity. In addition, metal halides are unstable under absorption conditions and after each loading/unloading cycle the breakthrough of the subsequent cycle decreases, making their use impractical for the time being [14]. Which is why there is still a lot of research to be done before this alternative can be commercially implemented.

1.4 Comparison of ammonia storage alternatives

Mature ammonia storage methods are currently available. As ammonia storage is a topic that has required vast research and development over decades, commercially available methods allow liquid ammonia to be stored from room to cryogenic temperature and from near atmospheric pressure to pressurisation [4].

The main factor determining the type of storage (pressurised, semi-refrigerated or refrigerated) is the ammonia storage capacity and is made on the basis of economics. For comparable large storage volumes, the capital investment costs for atmospheric pressure storage are substantially lower than for pressure storage. Despite higher energy costs for maintaining the pressure and for feed into and out of atmospheric storage, it is still more economical than pressurised storage. This applies especially to storage of ammonia coming from the synthesis loop (where low temperatures are needed for separating ammonia from the reactants) and loading/unloading of refrigerated vehicles [6]. This is why fully refrigerated tanks are used for storing large quantities of ammonia (up to 50,000 tonnes) [2] [3].

However, pressure storage is used to store small capacities that are required in downstream processes, in service storage for loading and unloading vehicles (truck, rail, marine) and for endpoints in pipeline systems. Horizontal cylindric tanks with hemispherical end caps are usually used for storing ammonia up to 150 tonnes, whereas spherical semi-refrigerated tanks are used for storing more substantial quantities, typically in the range of 250-1,500 tonnes [4]. Finally, semi-refrigerated storage is used in an intermediate capacity range up to 2,700 tonnes [8].

In addition to the storage capacity, the required conditions and the quantity of ammonia flowing in and out of storage (gaseous, warm liquid, cold liquid) are secondary factors to be considered [18]. In many cases, ammonia terminals-both for export from producing plants and for import from the distribution system-involve a combination of pressurised spheres and refrigerated storage tanks as ammonia is usually supplied at -33 °C to a ship or barge and at ambient temperature to pipeline or to rail or road transport vehicles [3].

Table 1 summarises characteristics of the three types of storage and the solid-state storage even though it is not commercially available yet.

Table 1: Characteristics of ammonia storage methods; based on [8]

Type	TRL	Typical pressure, bar	Design temperature, °C	t ammonia per t steel	Capacity, t ammonia	Refrigeration compressor
Pressure storage	9	16-18	20-25	2.8-6.5	<270 or <1,500	None
Semi-refrigerated storage	9	3-5	Ca. 0	10	450-2,700	Single stage
Low-temperature storage	9	1.1-1.2	-33	41-45	4,500-45,000 (<50,000)	Two-stage
Solid-state storage	3-4	1-30	20-250	-	-	None

2 FINAL CONDITIONING & TRANSPORT OF AMMONIA

Anhydrous ammonia as a global commodity is widely traded and transported through various distances [2]. Between 25 and 30 million tonnes of ammonia is transported annually [19]. Plants located in areas with abundant natural gas and low population density may transport close to 100% of their ammonia production or 40-60% if combined with some capacity to produce fertilisers [5]. Therefore, there is a large network of ports, ships, pipelines and dedicated storage facilities in ammonia producing and consuming countries and a high level of maturity regarding transport infrastructure.

Additionally, ammonia can also be transported using the current infrastructure of fossil fuels and equipment suitable for transporting LPG. Thus, facilities are often used interchangeably for transporting the two materials [20].

Liquid ammonia is transported in tankers, ships, barges, by pipelines, by railcars and by trucks. As it is almost always transported in the liquid state, it must either be compressed or refrigerated or some combination of the two [2].

2.1 Pipeline transportation

Transporting large quantities of ammonia by pipeline over long distances is more economical than transport by barge or rail, but the use of pipeline routes is limited to certain locations [4].

Long pipeline routes (>1,000 km) are mainly present in the United States, Russia, and Ukraine. In fact, the world's longest ammonia pipeline connects Russia and Ukraine. It has a total length of 2,424 km and can supply up to 2.5 million tonnes of ammonia per year. Normally, in long ammonia pipelines, automatic lock valves are installed at intervals of 16 km, so that the volume which can be released between two valves is limited to 400 tonnes [6].

Shorter routes (most of them shorter than 50 km) are more common across Europe where there is no significant ammonia pipeline transport as ammonia is mainly processed on site [6].

According to [4], the estimated cost of building the Gulf Central Pipeline in the United States was the equivalent to about $0.16 million/km in 2019. In the case of the Mid-America Pipeline (MAPCO), the equivalent cost is lower, around $0.08 million/km as the existing parallel liquefied petroleum gas and refined petroleum products pipeline infrastructure was used.

There are several important aspects to consider in this transport alternative, mainly related to the integrity of the pipelines. Ammonia transportation by pipelines requires the ammonia to be heated to at least 2 °C to avoid brittle fracture in the pipeline, which in most cases means that it must be warmed at the supply terminal and cooled again to -33 °C at the receiver terminal [5].

Ammonia shall also be transported at a minimum pressure of 20 bar to prevent gas formation [4]. This is because the vaporisation of some of the ammonia could reduce the transport capacity, make flow measurement and control difficult, and cause cavitation damage to the inner wall of the pipelines [21].

Additionally, the Interstate Commerce Commission requires that all anhydrous ammonia transported interstate in United States by pipeline contain at least 0.2 wt. % of water. This small amount of water is a corrosion inhibitor that limit the risk of stress corrosion cracking [5].

Regarding materials, steels are used in ammonia transfer lines. Stainless steel in particular is highly resistant to corrosion, but has the disadvantage of being very expensive. Materials such as copper, zinc, and aluminum are not used as they are easily corroded by ammonia [22].

2.2 Ocean and barge transportation

Regarding the transport volume, shipping of anhydrous ammonia is far more important than transport by rail. Overseas shipping gained great momentum through exports from producers in countries with low natural gas prices or low-price policies [6]. Between 18 and 20 million tonnes of ammonia are transported by ship annually [19]. Therefore, there is a high level of maturity in ammonia maritime transport infrastructure. International shipping routes are well established and there is a wide network of ports around the world handling ammonia on a large scale [21].

Ocean transportation of ammonia is done by ammonia tankers, river and coastal transportation by barges. Ammonia tankers are insulated and may be designed as semi-refrigerated (at 4 to 8 bar and around -10 °C) or mostly as fully refrigerated vessels (at near-atmospheric pressure and between -50 °C to -30 °C). Semi-refrigerated carriers typically contain up to 15,000 m³, while fully refrigerated carriers may transport as much as 50,000 tonnes [131]. Ammonia barges may have loading capacities of 400 to 2,500 tonnes and mostly have refrigerated load, but a few are pressure vessels (typically at 17-18 bar) [6].

The ships are equipped with refrigeration facilities which are similar to those of a storage facility. The ships are also equipped with pumps of sufficient capacity to discharge the ammonia at a rapid rate [2].

Ships within the range of 20,000-60,000 m³ are normally used for ammonia transportation, while ships larger than 60,000 m³ are generally employed for LPG transportation. Within the range of 20,000-30,000 m³ these vessels facilitate loading and unloading at origin and destination ports. Ships smaller than 20,000 m³ are mainly used for local, seaside, and short transportation of both LPG and ammonia. For ammonia transportation, barges in the range of 500-3,000 tonnes can be used. This is the case for many routes within Europe and the United States. In Europe mostly self- propelled barges are used to transfer ammonia through narrow and shallow inland waterways. In the United States most barge operations are along the Mississippi River and the seaside of the Gulf of Mexico [4].

The ammonia transportation freight cost depends on numerous factors such as the distance between the origin and target ports as well as on the availability of the ship, cargo size, fuel cost, crew cost, and terminal-related factors such as time spent in port and port operations (e.g., loading, receiving, storage, and transfer to and from the port). Furthermore, the cost can be affected by the LPG market (supply and demand), as the latter competes with ammonia on the use of such ships [4].

Regarding corrosion prevention, similar than in the case of ammonia transported by pipeline, in United States shipping containers constructed of quenched and tempered steel must contain minimum 0.2 wt. % of water [5].

2.3 Rail transportation

The distribution in rail cars and trucks primarily serves to supply smaller processing operations and wholesale merchants, is mainly used for shorter distances than pipeline or barge transportation, and may to some extent supplement large marine and pipeline shipments [6]. Examples of applications are the transport of ammonia from a pipeline or a large terminal to another storage terminal, transport between producers when one has an overproduction and the other a shortage [2], and its use in places without waterways and pipeline infrastructure [4].

Ammonia is transported by rail mainly in vehicles with capacities of 70-72 tonnes, although there are older vehicles of 25-30 tonnes and some larger of 90 tonnes [2]. However, the loading of ammonia is between 57%-85% of the tank's volume to avoid problems with thermal expansion in case the temperature increases [5].

Ammonia is transported as a pressurised liquid at a pressure of 15 to 16 bar and provided with pressure relief devices. Tanks usually have a thickness of 1.75 cm and are covered with a 0.32 cm jacket [4].

Normally, rail transport is more expensive than pipeline or barge per tonne/kilometre. According to [4], in some cases it can be cheaper than a combined pipeline/barge and truck transportation route. However, barge transportation has been proposed when possible as a replacement from rail transportation to minimise environmental impact, decreasing greenhouse gas emissions.

2.4 Truck transportation

Truck transportation is the most expensive method of transferring ammonia. However, it is mainly used worldwide for distances of less than 150 km or where other means of transport are not available [6]. One of the main applications of the truck transportation is to supply retail distribution centres or to small manufacturers of liquid fertilisers [2].

In general, the capacity of the trucks depends on the existing regulations in each country or region. Loading capacities range from 15 to 30 tonnes of ammonia in pressurised tanks with 10-28 bar.

2.5 Comparison of ammonia transport alternatives

Currently, the ammonia distribution network ranges from international transport of large quantities via ships or large pipelines to local transport via pipelines, trucks or rails enabling transport at retailer level. Even though it is a mature network, the development of new distribution lines or modernisation of existing ones will be critical as ammonia demand is expected to increase due to its traditional and new applications [4].

As mentioned in this section, the current options for ammonia transport are ship, barge, pipeline, rail and truck. The main aspects determining the transport mode are the available infrastructure, access, and cost. Furthermore, new policies to decrease greenhouse gas (GHG) emissions may shift some of the transported cargo from a relatively polluting mode such as trucks to a mode with lower emissions such as barges [4].

According to [2], there are some general considerations for selecting the most appropriate mean of ammonia transport:

- **Transportation by ship** is the only available option for overseas transport, and it also represents the lowest cost between two points significantly apart that are accessible to maritime shipping. However, ocean freight rates are likely to rise substantially and the cost of maritime terminals, harbour improvements, docks, jetties, etc., must be considered.

- **Barge transportation** is the most economical mean between points located on waterways that allow passage of tows of several large barges, e.g. for transport within a country or region with conveniently located ports or inland waterways and when shipping volume is enough to justify terminal costs. The main disadvantages are the restriction to points on navigable waterways and the fact that transport can be interrupted by ice, floods, and periods of low water. Therefore, terminal storage capacity must be increased to provide for these disruptions. This is why, costs of barge transportation depend more on the characteristics of the waterway than on the distance.

- Among the means of land transport, typically, **pipeline transport** is considerably cheaper than rail and truck. Pipeline transport is favoured by high volume use and by an even use pattern, which reduces storage terminal costs. Nevertheless, the cost of pipelines is important and varies widely depending on terrain and cost of acquiring right-of-way.
- **Transport by rail** is normally used for moderate quantities and rail can usually reach more points than pipelines. However, a suitable rail network must be available and, even so, the cost of suitable rail tank cars is substantial.

- **Trucks** are generally used for distribution over the final distance to the end-users as retailer-level transportation. This is usually the most expensive transport option, but as it is more flexible than other networks, it may be the only viable solution in some scenarios.

Finally, there are many cases where some combination of transport options must be considered along with storage terminals at transfer points. Additionally, when ammonia is not the end-product, the on-site processing and end-product transportation must also be evaluated.

3 REFERENCES

[1] P. Berwal, S. Kumar and B. Khandelwal, “A comprehensive review on synthesis, chemical kinetics, and practical application of ammonia as future fuel for combustion,” Journal of the Energy Institute, vol. 99, p. 273-298, 2021.

[2] H. TP, “Transportation and storage of ammonia,” in Fertilizer Manual, Springer Netherlands, 1985, pp. 73-82.

[3] A. Nielsen, “Chapter 6. Ammonia Production Processes,” in Ammonia, Springer, Berlin, Heidelberg, 1995, p. 199-327.

[4] O. ELISHAV, B. M. LIS, A. VALERA-MEDINA and G. GRADER, “Storage and Distribution of Ammonia,” in Techno-Economic Challenges of Green Ammonia as an Energy Vector, 2021, pp. 85-103.

[5] A. Nielsen, “Ammonia Storage and Transportation-Safety,” in Ammonia, Springer, Berlin, Heidelberg, 1995, p. 329-346.

[6] M. APPL, “Ammonia, 1. Introduction,” in Ullmann's Encyclopedia of Industrial Chemistry, Dannstadt-Schauernheim, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2012, pp. 107-133.

[7] S. CROLIUS, D. PUGH, S. MORRIS and A. VALERA-MEDINA, “Safety Aspects,” in Techno-Economic Challenges of Green Ammonia as an Energy Vector, Elsevier Inc., 2020, pp. 221-257.

[8] K. H. Rouwenhorsta, A. G. V. d. Hamb, G. Mulc and S. R. Kerstenb, “Islanded ammonia power systems: Technology review & conceptual process design,” Renewable and Sustainable Energy Reviews, vol. 114, 2019.

[9] S. Giddey, S. Badwal and A. Kulkarni, “Review of electrochemical ammonia production technologies and materials,” International journal o f hydrogen energy, vol. 38, pp. 14576-14594, 2013.

[10] C. Philibert, “Renewable Energy for Industry. From green energy to green materials and fuels,” OECD/IEA, 2017.

[11] A. Klerke, C. H. Christensen, J. K. Nørskovb and T. Vegge, “Ammonia for hydrogen storage: challenges and opportunities,” J. Mater. Chem., vol. 18, no. 20, p. 304-2310, 2008.

[12] DAN WEBB; MGR., ENG. & TECH. SVCS.; CF INDUSTRIES, INC., “LARGE SCALE AMMONIA STORAGE AND HANDLING,” LONG GROVE, IL.

[13] T. Zhanga, H. Miyaokaa, H. Miyaoka, T. Ichikawa and Y. Kojima, “A Review on Ammonia Absorption Materials: Metal Hydrides, Halides, and Borohydrides,” ACS Applied Energy Materials, 2018.

[14] M. Malmali, G. Le, J. Hendrickson, J. Prince, A. V. McCormick and E. L. Cussler, “Better Absorbents for Ammonia Separation,” ACS Sustainable Chem. Eng., pp. 1-27, 2018.

[15] O. Osman, S. Sgouridis and A. Sleptchenko, “Scaling the production of renewable ammonia: A techno-economic optimization applied in regions with high insolation,” Journal of Cleaner Production, vol. 271, 2020.

[16] T. Aoki, T. Ichikawa, H. Miyaoka and Y. Kojima, “Thermodynamics on Ammonia Absorption of Metal Halides and Borohydrides,” The Journal of Physical Chemistry, vol. 118, pp. 18412-18416, 2014.

[17] D. Chakraborty, H. N. Petersen, C. Elkjær, A. Cagulada and T. Johannessen, “Solid ammonia as energy carrier: Current status and future prospects,” Fuel Cells Bulletin, 2009.

[19] IRENA and AEA, “Innovation Outlook: Renewable Ammonia,” International Renewable Energy Agency, Abu Dhabi, Ammonia Energy Association, Brooklyn., 2022.

[20] Toward future zero carbon emissions,” International journal of hydrogen energy, vol. 48, pp. 11237-11273, 2023.

[21] J. Fuster Justiniano, Y. Arteaga Guaquín and R. Farías Hermosilla, “Industria del Amoníaco: estado actual y oportunidades para la descarbonización,” Santiago de Chile, 2022.

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