



The Large Scale Green Ammonia Value Chain

A high-level multi aspect assessment



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Executive Summary (English)

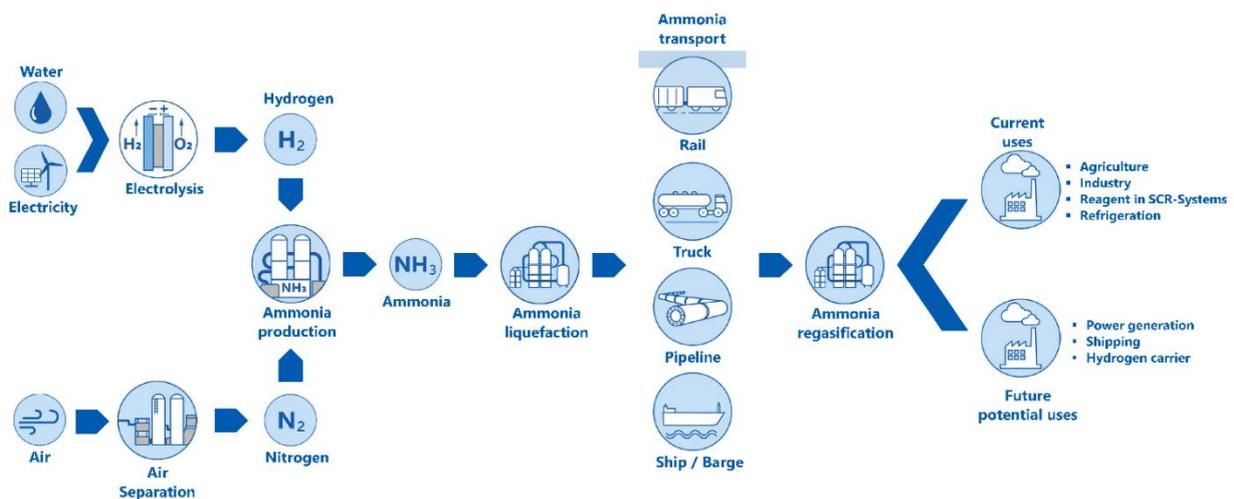
The production of ammonia (NH₃) has grown steadily over the years, reaching approximately 186 Mt in 2020, according to the international fertilizer association. More than 50% of this ammonia was produced in Asia and Russia. North America also had a substantial share, accounting for 12% of the worldwide production, while being followed by the Middle East with 9%. Nearly all this ammonia is generated from fossil fuels, leading to yearly life-cycle emissions of 0.5 Gt of carbon dioxide.

The Green Ammonia Value Chain

In the coming years, the increasing population and rising affluence worldwide will drive the need for more ammonia. However, this surge in demand coincides with governments worldwide committing to achieving net-zero emissions in the energy sector. Therefore, pressure is mounting to find sustainable solutions that meet the growing ammonia demand, while minimizing environmental impact. Furthermore, the expansion of the usage of low carbon ammonia into new sectors can serve as a foundation for enabling the worldwide adoption of low carbon hydrogen in different industries.

Chile, a country abundant in renewable energy resources, is anticipated to play a vital role to this endeavor. With the launch of the green hydrogen national strategy in 2020, Chile aims to position itself at the forefront of green hydrogen and its derivatives. Projections indicate a market size of \$5 billion USD for Chilean green ammonia exports by 2050. Hence, the focus of the value chain presented in Figure 0-1 and discussed in this report, is green ammonia. It is important to mention that the differentiating factor in the green ammonia lies only in the ammonia synthesis block (more specifically, in the hydrogen production for ammonia), whereas all other aspects discussed in this report (transport, storage as well as handling and safety) are identical for the other low carbon form of ammonia, so-called blue ammonia.

Figure 0-1 The green ammonia value chain



The green NH₃ value chain begins with the supply of hydrogen (H₂). Towards achieving a CO₂-free energy system, the focus is solely on decarbonized H₂. In the context of green ammonia, electrolyzers are deployed, which produce carbon-free H₂ through the splitting of water in hydrogen and oxygen, the so-called electrolysis, using electricity from renewable energy sources. The second fundamental element in ammonia production is nitrogen. Nitrogen is taken out of the air, as its share is >75% by weight. Its local production can be divided in mainly three technologies, Pressure Swing-Adsorption (PSA), Air Separation Unit (ASU) and Membrane systems, each one with different technical characteristics, capacities and quality standards. The final step in

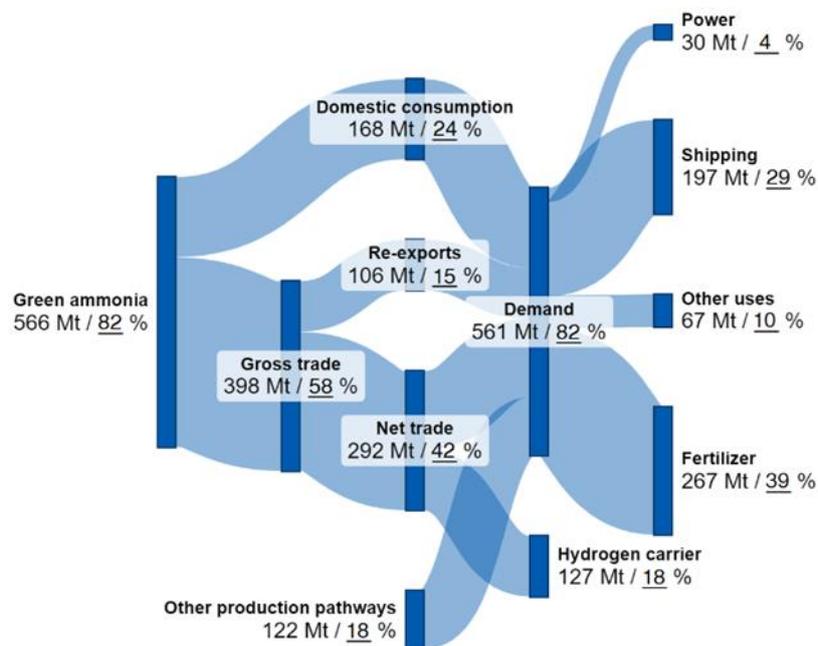
the upstream block is ammonia synthesis. The produced elemental nitrogen and hydrogen react by the presence of an iron-based catalyst, following the equation:



The process is called Haber-Bosch based on its inventors, Fritz Haber and Carl Bosch and, although process technology has been improved over the years, there have been no fundamental changes in the chemical reaction itself, which dates to the 1910s. The ammonia synthesis is an exothermic reaction that occurs naturally at low temperature. Industrial reactor conditions for ammonia synthesis typically involve temperatures ranging from 350-550°C and pressures ranging from 100-460 bar.

Subsequently, the green ammonia must be transported to its end-users for consumption. A globally traded commodity, ammonia has been handled in large quantities for several decades, and as a result, there is already a high maturity of storage, transport, and distribution technologies. Since it is gaseous at ambient conditions, but being relatively easy liquefied, ammonia is always being handled as a liquid throughout the transport chain. Transportation methods include trucks, trains and pipelines as well as ships and barges when water bodies and rivers shall be crossed. Of course, storage is required at various stages of the ammonia value chain to balance supply and demand: At synthesis plants, tanks hold ammonia before transport. Ports, as import/export hubs, rely on storage for efficient logistics and distribution despite production or shipping delays. End-user facilities also maintain on-site storage for their own needs.

Figure 0-2 Green ammonia production projection in 2050 based on IRENA's 1.5°C scenario



Approximately 85% of the current ammonia production is dedicated to the manufacturing of synthetic nitrogen fertilizers. The remainder is distributed to diverse applications, including refrigeration, mining, pharmaceuticals, water treatment, plastics, and fibers, as well as the abatement of nitrogen oxides (NO_x). Beyond these, research is focused on expanding ammonia's role in power generation, shipping, and as a hydrogen carrier. Under IRENA's 1.5°C scenario, annual green ammonia production could reach 566 Mt by 2050, with these emerging sectors expected to drive 354 Mt of that demand.

Noteworthy to mention, that this developing ammonia market is witnessing the emergence of import and export countries, with the latter being characterized by their abundant renewable potential. Countries like Chile and Australia, with their vast renewable resources, are positioned as key players in ammonia export. On the other

side, Germany for instance, with a growing demand for hydrogen and its derivatives, but with limited domestic renewable energy potential, is projected as an importer. To facilitate the same and equal playing field for the various stakeholders in this developing market, appropriate certifications schemes for the decarbonized fuels, including of course ammonia, are crucial. The goal of those schemes is to track the associated entire (life cycle) emissions of the subject fuels based on well-proven methodologies.

Focus on Production

Prominent ammonia licensors, which already hold a significant market share in the current ammonia industry, are now focusing on developing decarbonized solutions for ammonia synthesis. Notable examples of these licensors include Stamcarbon, KBR, Topsoe, Casale, and ThyssenKrupp. Some of those licensors additionally conduct EPC services (e.g., KBR, ThyssenKrupp). Ammonia synthesis is a well-established process. The major technical challenge in green ammonia production lies in the design and operation of a facility that sources its hydrogen from renewable power resources rather than fossil fuels. Unlike fossil-based feedstock streams like natural gas, renewable power generation is intermittent and consequently, the hydrogen supply to the ammonia synthesis loop is to some extent also fluctuating. Therefore, the technology providers nowadays try to enhance the flexibility of the ammonia synthesis loop, focusing on different process control technologies to achieve a well-integrated operation of all the process blocks. For smaller to medium plant sizes, up to ≈ 600 Metric Tonnes per Day (MTPD), modularized (prefabricated) concepts are commonly offered by the licensors, allowing quick on-site installation and scalability. For larger plants, the solutions are tailor-made to the specific project needs to cut down on costs and based on the “stick built” principle. Another interesting fact of the green ammonia synthesis loop, compared to the currently operated fossil fuel driven ones, is the use of an electric start-up heater instead of a gas-fired one. The role of a start-up heater is to bring and keep the system within the elevated temperature range. The use of an electric start-up heater enhances the sustainability potential of the process.

Focus on Transport

As an internationally traded chemical, ammonia offers various well-established transport options that cater to different scales, distances, and desired continuity of supply. Those are presented in Table 0-1.

Table 0-1 Comparison of ammonia transport technologies

Method	Distance	Quantity per one way Trip	Continuity of Supply
Shipping	Long overseas transport.	Large quantities up to 50,000 tonnes.	No continuous supply, prone to: <ul style="list-style-type: none"> • Adverse weather conditions (wind). • Port congestion.
Barge	Inland waterways or coastal shipping.	Large quantities up to 3,000 tonnes.	No continuous supply, prone to: <ul style="list-style-type: none"> • Adverse weather conditions (draught, flood, ice in water ways). • Port congestion.
Pipeline	From short stretches to up to 3,000 km. ¹	Covers the whole range, from small to large quantities.	Continuous and uninterrupted supply.
Rail	Short or long distances, provided the rail infrastructure availability and interconnections.	Can reach large quantities in the range	Intermittent supply.

¹ Taking as a reference the Gulf Central Pipeline, the longest ammonia pipeline worldwide.

Method	Distance	Quantity per one way Trip	Continuity of Supply
		of 4,000 tonnes per trip and even more. ²	
Truck	Maximum 150-200 km, restricted by economics.	Small quantities, up to 30 tonnes.	Intermittent supply.

Trucks are primarily utilized for short distances, typically up to a maximum of 200 km, due to the higher transport costs associated with smaller volumes of ammonia being transported. As such, main applications of the truck transportation are to supply retail distribution centres or small manufacturers of liquid fertilisers. An ammonia tank for trucks can carry up to 30 tonnes of ammonia in fully pressurized conditions. Their most significant advantage as method of transport is that they can reach every off-taker, even in the most remote areas.

Rail transport, on the other hand, can accommodate medium-scale transportation, allowing for significantly larger quantities compared to trucks, as several Rail Tank Cars (RTCs) can be carried via a single locomotive, reaching quantities in the range of 4,000 tonnes per trip. The volume capacity of RTCs spans from 50 to 110 m³, whereas the ammonia is stored in fully pressurized conditions. Trains can serve short to quite long distances, provided the existence of railway infrastructure and interconnections. In both the cases of rail transport and truck (road tanker) transport, the issue of empty return trips is a significant concern, as it reduces the cost efficiency.

Shipping is the only method for large-scale overseas transport of ammonia. Overseas shipping of ammonia is a well-established business all over the world. Around 18-20 Mt of ammonia are transported annually by ship. Globally, around 170 ships are in operation that can carry ammonia, of which 40 carry ammonia on a continuous basis (Brown, 2019) (Hatfield, 2020). Currently, the largest ammonia carrier can transport approximately 50,000 tonnes of ammonia, with ongoing efforts for larger classes, which will be able to serve the expected import targets, while avoid congestion at high volume terminals, such as Rotterdam. Due to economic reasons, ammonia ship storages are based on full-refrigerated conditions.

Barges are suitable for transportation along inland waterways and coastal areas. They have capacities in the range of 500-3,000 tonnes, with the larger ones being fully refrigerated and the smaller ones being semi-refrigerated. One drawback of barge transportation on rivers is the potential for interruptions caused by ice, floods, and low water levels.

Lastly, pipelines are the most versatile method of transportation, capable of covering both short and long distances, as well as transporting small to very large quantities, while operating 24/7. Ammonia pipelines are a mature technology worldwide, with the USA having the largest related infrastructure, totalling approx. 4,950 km. For lengths up to commonly 5 km, the ammonia pipelines are fully refrigerated, whereas for longer pipelines, those operate under fully pressurized conditions due to heat losses. The main barrier to pipeline infrastructure is the significant initial expenses and the time-consuming construction process.

² Maximum ammonia cargo per trip depends highly on the capacity of the RTC deployed as well as on the in-force regulations in each country, which vary considerably in terms of maximum length per train.

Focus on Storage

The applied ammonia storage technologies accompanied by their main technical characteristics are presented in Table 0-2 Comparison of ammonia storage technologies

Table 0-2 Comparison of ammonia storage technologies

Method	Typical pressure (bar)	Design temp. (°C)	t_{NH_3} / t_{steel} (-)	Storage capacity (kt_{NH_3})	Refrigeration System
Non-refrigerated (fully pressurized)	16-25	20-25	2.8	<1.5	None
Semi-refrigerated	3-5	0	10	0,5-2.7	Single stage
Fully-refrigerated (non-pressurized)	1.2	-33	41-45	5-45	Two stages

Fully-pressurized storage is performed at ambient temperatures and high pressures. To maintain ammonia in a liquid state at an ambient temperature of 20°C, a pressure of 8.58 bar_g is required. However, in pressure storage vessels, ammonia is kept at an even higher pressure to ensure it remains in a liquid state even if the ambient temperature rises to elevated levels, such as in desert-like environments. Pressure vessels can be cylindrical with capacities up to 150 tons or spherical with weights ranging from 250 to 1,500 tons. Pressurized storage is simpler than refrigerated storage, as it does not require refrigeration systems, and as such, is preferred in the case of mobile storage in the case of rail or road transport. Nurse tanks and T50 ISO tanks are types of fully pressurized ammonia storage that are deployed for agricultural applications and transport, respectively.

Fully refrigerated ammonia storage is performed at low temperatures and ambient pressures. This storage method allows for the slow evaporation of ammonia over time due to the heat transferred from the environment, which is known as boil-off gas (BOG). Therefore, a two-stage refrigeration system is necessary to preserve the ammonia at a low temperature and to cool it upon entry to the storage facility. This system uses the stored ammonia directly as the refrigerant in the refrigeration cycle. The fully refrigerated storage type significantly reduces the steel content of the vessel, requiring approximately 15 times less steel compared to fully pressurized storage. This results in reduced capital costs. Despite the higher energy consumption associated with double-stage refrigeration, fully refrigerated storage is widely adopted for large-scale ammonia storage in production sites and export/import ammonia terminals. Currently, a 45,000 tons tank is considered the upper threshold for state-of-the-art tanks, but this may be increased in the future.

Lastly, semi-refrigerated ammonia tanks can reach capacities of up to 2,700 tonnes, serving small to medium-scale applications. These tanks are commonly used in applications such as barges and factories. Similarly to fully refrigerated storage, boil-off gas (BOG) occurs at typical storage temperatures close to 0°C. However, due to the lower cooling requirements compared to fully refrigerated storage, a single refrigeration stage is sufficient for semi-refrigerated tanks.

Focus on Safety

The safety aspects of ammonia relate strongly to the overall volume at hand as well as the pressure and temperature under which the ammonia is contained in the various components of the plant. Obviously, when considering storage of any type, irrespective of whether moving or static storage is concerned, this is where the safety risks for the larger part lie. In a more general context, it makes sense to split the relevant codes & standards between those purely pertaining to safety, environmental and health related (managerial) matters and those which primarily are relevant for the technical design and engineering of the facilities. There is, however, a strong relation between both types of standards as the input and output is generated between them. The responsibility for the health & safety of personnel and for the health & safety and protection of the

environment and the public, lies foremost with the facility owner / operator. Guidance in fulfilling these requirements is offered by (inter)national institutions, regulators and knowledge institutes as well as the respective industry itself. The basic but pivotal means of supporting this responsibility is the setup of a Safety Management System.

On the other side, with regards to achieving an intrinsically safe design, a multitude of codes and standards are applicable as minimum requirements to the design, procurement and construction phases of ammonia facilities, as well as the operation & maintenance of the plant.

Conclusions and Recommendations

As the demand for ammonia is projected to significantly increase, there is a need for sustainable solutions to meet this demand while reducing emissions and minimizing environmental impact. To realize this ambitious undertaking and move to a green ammonia value chain, a multitude of steps is necessary:

1. **Governments:** Regulation has a pivotal role to play in shaping a sustainable and low-emission future. The current slow-down in green ammonia project development can be attributed to the lack of a clear business case for producers. For consumers, carbon-emitting alternatives are still cheaper than green ammonia and a framework to cover the cost difference does not exist. Hence, the general market framework is still such that using green ammonia is not attractive to consumers. Mechanisms such as Germany's H2Global's auction for green ammonia or Japan's JERA auctions for low carbon ammonia have provided tangible results for some projects. These are, however, limited quantities. A reliable pathway towards a framework enabling a green ammonia market is still under development, causing uncertainty for project developers and hence investment decisions are not taken. Developing a playing field that gives green ammonia project developers a clear business case is therefore the key task for governments in enabling the market ramp-up.
2. **Research and Development:** The individual technologies of the upstream block of the ammonia value chain, i.e., electrolysis and ammonia synthesis, have existed since decades. For example, alkaline electrolysis is entirely mature, having a TRL of 9, where the same applies to ASU and ammonia synthesis facilities. The novelty is found in the combination of these technologies at scale, combining intermittency (RES) with normally considered steady state processes (ammonia synthesis). The deployment of large-scale green ammonia plants can be expected to result in a significant learning curve regarding the dynamic behavior of the process components and their interaction. Since large-scale green ammonia projects are first-of-its-kind plants, collaborative projects and partnerships are key to fostering needed development and risk mitigation. Lastly, accumulating knowledge through smaller sized projects as well as decentralized applications, can pave the way towards the desired up-scaling of the PtX plants.
3. **Infrastructure Development:** The ammonia industry benefits from its extensive infrastructure that spans across all aspects of the value chain, including production, transportation, storage, and handling. With this solid foundation, the industry is well-prepared to expand its infrastructure to cater to the increasing demands of the future. Nonetheless, one area of focus for the industry should be the ammonia cracking, a process required to facilitate the usage of green ammonia as a hydrogen carrier. While various OEMs are currently intensively researching decarbonized ammonia cracking, the technology is not yet ready for large-scale commercial use and therefore, further advancements are needed. Moreover, due to the large scale and costly nature of infrastructure projects such as ammonia import/export terminals and long pipeline systems, public financing mechanisms and support will be required. Lastly, in locations where multiple green ammonia production projects are being realized, the concept of shared infrastructure should be considered. By sharing resources and facilities, the costs can be distributed amongst the projects, making them more economically viable. Besides, this approach allows for the benefits of economy of scale, achieving greater efficiencies and cost savings.
4. **Safety:** Ammonia has been handled as a chemical substance for more than a century, and this extensive experience has resulted in a high level of safety and technical efficiency. In fact, the handling

of ammonia has consistently improved in terms of safety. Technological advancements have enhanced measuring and inspection capabilities, while lessons learned have been applied to bring the industry to its present state. However, ammonia, as well as other decarbonized fuels like methanol and hydrogen, being less known to the population, might be seen to be more dangerous. This is also evident in the cautious approach taken by some import / export ports when it comes to developing ammonia infrastructure, stemming from environmental and safety concerns.

5. Certification schemes: Such schemes play a crucial role in advancing the development of decarbonized fuels, including green ammonia. Many countries, whether acting as exporters or importers, are actively working on establishing certification frameworks to ensure a level playing field for all stakeholders involved. These schemes provide proof that specific methodologies and analytical frameworks are being followed in accordance with defined standards and requirements. As a result, credibility and transparency are established, and consumers can be assured that a certified product or service meets their expectations. Of course, there is a need of harmonization and mutual recognitions of those schemes to enable the free flow of decarbonized fuels across borders and avoid market barriers that hinder the ammonia trade.
6. International Collaboration: Collaboration between technology providers, industries, and research institutions is crucial for sharing knowledge, implementing best practices, and driving the widespread adoption of green ammonia technologies worldwide. Given the nature of this emerging market, it is essential for both importing and exporting countries to form international partnerships that will facilitate the trade.

Resumen Ejecutivo (Español)

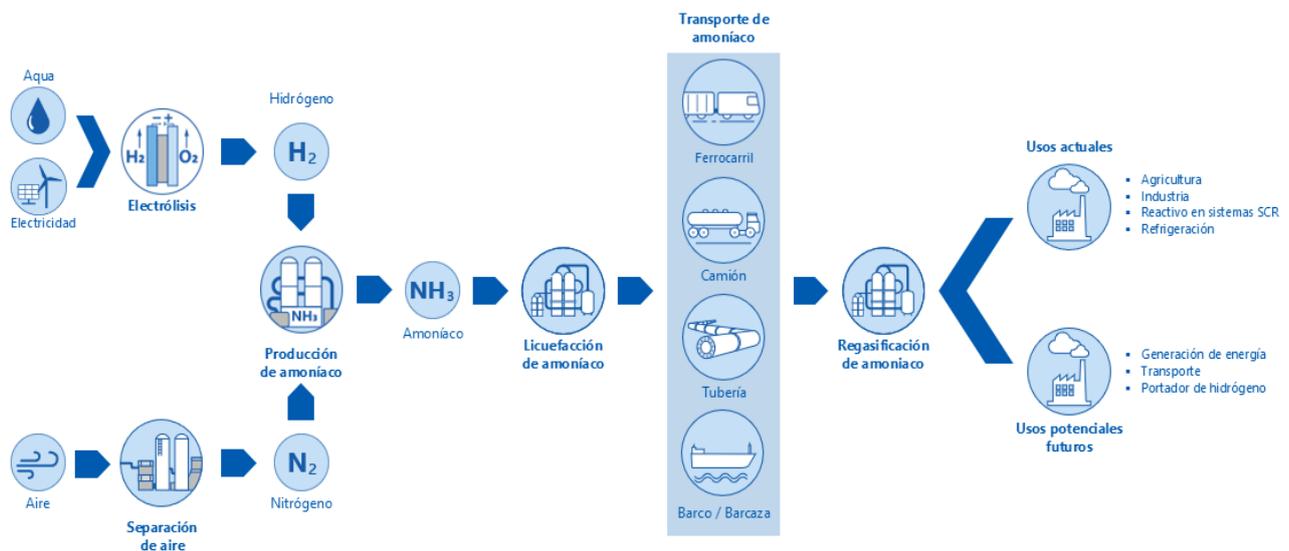
La producción de amoníaco (NH_3) no ha dejado de crecer a lo largo de los años, hasta alcanzar aproximadamente 186 Mt en 2020, según la asociación internacional de fertilizantes. Más del 50% de este amoníaco se produjo en Asia y Rusia. América del Norte también tuvo una cuota sustancial, con un 12% de la producción mundial, seguida de Oriente Medio con un 9%. Casi todo este amoníaco se genera a partir de combustibles fósiles, lo que supone unas emisiones anuales de 0,5 Gt de dióxido de carbono durante su ciclo de vida.

La cadena de valor del amoníaco verde

En los próximos años, el aumento de la población y de la riqueza en todo el mundo impulsará la necesidad de más amoníaco. Sin embargo, este aumento de la demanda coincide con el compromiso de los gobiernos de todo el mundo de lograr emisiones netas cero en el sector energético. Por lo tanto, aumenta la presión para encontrar soluciones sostenibles que satisfagan la creciente demanda de amoníaco, minimizando al mismo tiempo el impacto medioambiental. Además, la expansión del uso de amoníaco bajo en carbono en nuevos sectores puede servir de base para permitir la adopción mundial de hidrógeno bajo en carbono en diferentes industrias.

Se prevé que Chile, un país con abundantes recursos energéticos renovables, juegue un papel vital en este empeño. Con el lanzamiento de la estrategia nacional de hidrógeno verde en 2020, Chile pretende situarse a la vanguardia del hidrógeno verde y sus derivados. Las proyecciones indican un tamaño de mercado de 5.000 millones de dólares para las exportaciones chilenas de amoníaco verde en 2050. De ahí que la cadena de valor presentada en la Figura 0-1 y analizada en este informe, es el amoníaco verde. Es importante mencionar que el factor diferenciador del amoníaco verde reside únicamente en el bloque de síntesis del amoníaco (más concretamente, en la producción de hidrógeno para amoníaco), mientras que todos los demás aspectos tratados en este informe (transporte, almacenamiento, así como manipulación y seguridad) son idénticos para la otra forma de amoníaco con bajas emisiones de carbono, el denominado amoníaco azul.

Figura 0-1 Cadena de valor de amoníaco verde



La cadena de valor del NH_3 verde comienza con el suministro de hidrógeno (H_2). Para conseguir un sistema energético libre de CO_2 , la atención se centrará exclusivamente en el H_2 descarbonizado. En el contexto del amoníaco verde, se utilizan electrolizadores que producen H_2 libre de carbono mediante la división del agua en hidrógeno y oxígeno, la denominada electrólisis, utilizando electricidad procedente de fuentes de energía renovables. El segundo elemento fundamental en la producción de amoníaco es el nitrógeno. El nitrógeno se extrae del aire, ya que su proporción es $>75\%$ en peso. Su producción local puede dividirse principalmente

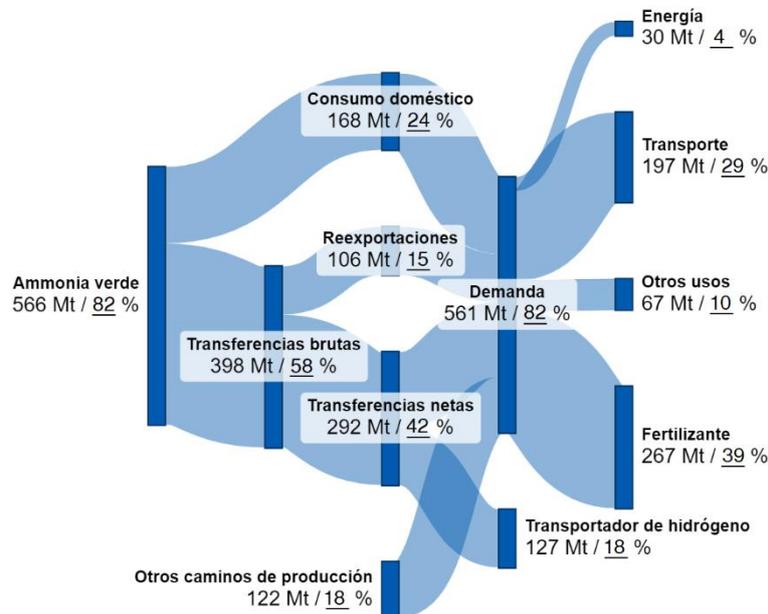
en tres tecnologías, la adsorción por cambio de presión (PSA), la unidad de separación del aire (ASU) y los sistemas de membrana, cada una con características técnicas, capacidades y normas de calidad diferentes. El último paso del bloque anterior es la síntesis de amoníaco. El nitrógeno elemental y el hidrógeno producidos reaccionan en presencia de un catalizador a base de hierro, siguiendo la ecuación:



El proceso se denomina Haber-Bosch por sus inventores, Fritz Haber y Carl Bosch y, aunque la tecnología del proceso se ha mejorado con los años, no ha habido cambios fundamentales en la reacción química en sí, que se remonta a la década de 1910. La síntesis del amoníaco es una reacción exotérmica que se produce de forma natural a baja temperatura. Las condiciones de los reactores industriales para la síntesis de amoníaco suelen implicar temperaturas que oscilan entre 350 y 550°C y presiones que oscilan entre 100 y 460 bares.

Posteriormente, el amoníaco verde debe transportarse hasta los usuarios finales para su consumo. El amoníaco, una mercancía comercializada en todo el mundo, se manipula en grandes cantidades desde hace varias décadas, por lo que ya existe una gran madurez de las tecnologías de almacenamiento, transporte y distribución. Al ser gaseoso en condiciones ambientales, pero relativamente fácil de licuar, el amoníaco se manipula siempre como líquido a lo largo de toda la cadena de transporte. Los métodos de transporte incluyen camiones, trenes y tuberías, así como barcos y barcasas cuando hay que atravesar cuerpos de agua y ríos. Por supuesto, el almacenamiento es necesario en varias fases de la cadena de valor del amoníaco para equilibrar la oferta y la demanda: En las plantas de síntesis, los tanques almacenan el amoníaco antes del transporte. Los puertos, como centros de importación y exportación, dependen del almacenamiento para una logística y distribución eficientes a pesar de los retrasos en la producción o el transporte. Las instalaciones de los usuarios finales también mantienen un almacenamiento in situ para sus propias necesidades.

Figura 0-2 Proyección de la producción de amoníaco verde en 2050 basada en el escenario de 1,5 °C de IRENA



Aproximadamente el 85% de la producción actual de amoníaco se dedica a la fabricación de fertilizantes nitrogenados sintéticos. El resto se distribuye a diversas aplicaciones, como la refrigeración, la minería, los productos farmacéuticos, el tratamiento de aguas, los plásticos y las fibras, así como la reducción de los óxidos de nitrógeno (NO_x). Además, la investigación se centra en ampliar el papel del amoníaco en la generación de energía, el transporte marítimo y como portador de hidrógeno. En el escenario de 1,5 °C de

IRENA, la producción anual de amoníaco ecológico podría alcanzar las 566 Mt en 2050, y se espera que estos sectores emergentes impulsen 354 Mt de esa demanda.

Cabe mencionar que este mercado del amoníaco en desarrollo está siendo testigo de la aparición de países importadores y exportadores, caracterizándose estos últimos por su abundante potencial renovable. Países como Chile y Australia, con sus vastos recursos renovables, se posicionan como actores clave en la exportación de amoníaco. En el lado opuesto, Alemania, por ejemplo, con una demanda creciente de hidrógeno y sus derivados, pero con un potencial nacional de energías renovables limitado, se proyecta como importador. Para facilitar la igualdad de condiciones a las distintas partes interesadas en este mercado en desarrollo, es crucial contar con sistemas de certificación adecuados para los combustibles descarbonizados, incluido, por supuesto, el amoníaco. El objetivo de estos sistemas es hacer un seguimiento de todas las emisiones asociadas (ciclo de vida) de los combustibles en cuestión basándose en metodologías probadas.

Foco en la producción

Los principales licenciatarios de amoníaco, que ya poseen una cuota de mercado significativa en la industria actual del amoníaco, se están centrando ahora en el desarrollo de soluciones descarbonizadas para la síntesis de amoníaco. Algunos ejemplos notables de estos licenciatarios son Stamicarbon, KBR, Topsoe, Casale y ThyssenKrupp. Algunos de estos licenciantes prestan además servicios de EPC (por ejemplo, KBR, ThyssenKrupp). La síntesis de amoníaco es un proceso bien establecido. El principal reto técnico de la producción ecológica de amoníaco reside en el diseño y el funcionamiento de una instalación que obtiene su hidrógeno de fuentes de energía renovables en lugar de combustibles fósiles. A diferencia de los flujos de materias primas fósiles, como el gas natural, la generación de energía renovable es intermitente y, en consecuencia, el suministro de hidrógeno al circuito de síntesis de amoníaco también fluctúa en cierta medida.

Por ello, los proveedores de tecnología intentan hoy en día mejorar la flexibilidad del bucle de síntesis de amoníaco, centrándose en diferentes tecnologías de control de procesos para lograr un funcionamiento bien integrado de todos los bloques del proceso. Para plantas pequeñas y medianas, de hasta \approx 600 toneladas métricas por día (TMPD), los licenciantes suelen ofrecer conceptos modularizados (prefabricados) que permiten una rápida instalación in situ y escalabilidad. En el caso de plantas más grandes, las soluciones se adaptan a las necesidades específicas del proyecto para reducir costes y se basan en el principio de "construcción en serie". Otro aspecto interesante del bucle verde de síntesis de amoníaco, comparado con los que funcionan actualmente con combustibles fósiles, es el uso de un calentador eléctrico de arranque en lugar de uno de gas. La función de un calentador de arranque es mantener el sistema a una temperatura elevada. El uso de un calentador eléctrico de arranque aumenta el potencial de sostenibilidad del proceso.

Foco en el transporte

Como producto químico comercializado internacionalmente, el amoníaco ofrece varias opciones de transporte bien establecidas que se adaptan a diferentes escalas, distancias y continuidad de suministro deseada. Estas opciones se presentan en Tabla 0-1.

Tabla 0-1 Comparación de las tecnologías de transporte de amoníaco

Método	Distancia	Cantidad por viaje de ida	Continuidad del suministro
Envío	Largo transporte al extranjero.	Grandes cantidades, hasta 50.000 toneladas.	No hay suministro continuo. Propenso a: <ul style="list-style-type: none"> • Condiciones meteorológicas adversas (viento). • Congestión portuaria.
Barcaza	Navegación interior o costera.	Grandes cantidades de hasta 3.000 toneladas.	No hay suministro continuo. Propenso a: <ul style="list-style-type: none"> • Condiciones meteorológicas adversas (sequía,

			<p>inundaciones, hielo en las vías navegables).</p> <ul style="list-style-type: none"> • Congestión portuaria.
Tuberías	Desde tramos cortos hasta 3.000 km. ³	Cubre toda la gama, desde pequeñas a grandes cantidades.	Suministro continuo e ininterrumpido.
Ferrocarril	Distancias cortas o largas, siempre que se disponga de infraestructura ferroviaria y de interconexiones.	Puede alcanzar grandes cantidades del orden de 4.000 toneladas por viaje e incluso más. ⁴	Suministro intermitente.
Camión	Máximo 150-200 km, limitado por la economía.	Pequeñas cantidades, hasta 30 toneladas.	Suministro intermitente.

Los camiones se utilizan principalmente para distancias cortas, normalmente hasta un máximo de 200 km, debido a los mayores costes de transporte asociados a los volúmenes más pequeños de amoníaco que se transportan. Por ello, las principales aplicaciones del transporte en camión son el suministro a centros de distribución minorista o a pequeños fabricantes de fertilizantes líquidos. Una cisterna de amoníaco para camiones puede transportar hasta 30 toneladas de amoníaco en condiciones totalmente presurizadas. Su ventaja más significativa como método de transporte es que pueden llegar a todos los consumidores, incluso en las zonas más remotas.

El transporte ferroviario, por su parte, permite transportar cantidades significativamente mayores que los camiones, ya que una sola locomotora puede transportar varios vagones cisterna ferroviarios (RTC), alcanzando cantidades del orden de 4.000 toneladas por viaje. La capacidad volumétrica de los RTC oscila entre 50 y 110 m³, mientras que el amoníaco se almacena en condiciones totalmente presurizadas. Los trenes pueden dar servicio a distancias cortas o bastante largas, siempre que existan infraestructuras ferroviarias e interconexiones. Tanto en el caso del transporte ferroviario como en el del transporte por camión (cisterna), el problema de los viajes de ida y vuelta vacíos es una preocupación importante, ya que reduce la rentabilidad.

El transporte marítimo es el único método para transportar amoníaco a gran escala. El transporte marítimo de amoníaco es una actividad consolidada en todo el mundo. Cada año se transportan por barco entre 18 y 20 Mt de amoníaco. En todo el mundo operan unos 170 buques que pueden transportar amoníaco, de los cuales 40 transportan amoníaco de forma continua (Brown, 2019) (Hatfield, 2020). Actualmente, el mayor transportista de amoníaco puede transportar aproximadamente 50.000 toneladas de amoníaco, con esfuerzos en curso para clases más grandes, que podrán servir a los objetivos de importación esperados, evitando al mismo tiempo la congestión en terminales de gran volumen, como Rotterdam. Por razones económicas, el almacenamiento de amoníaco en los buques se realiza en condiciones de refrigeración total.

Las barcazas son adecuadas para el transporte por vías navegables interiores y zonas costeras. Su capacidad oscila entre 500 y 3.000 toneladas, siendo las más grandes totalmente refrigeradas y las más pequeñas semi refrigeradas. Algunos de los inconvenientes del transporte fluvial en barcaza son las posibles interrupciones causadas por el hielo, las inundaciones y el estiaje.

Por último, los gasoductos son el método de transporte más versátil, capaz de cubrir tanto distancias cortas como largas, así como de transportar cantidades pequeñas o muy grandes, funcionando las 24 horas del día, los 7 días de la semana. Los gasoductos de amoníaco son una tecnología madura en todo el mundo, siendo

³ Tomando como referencia el oleoducto Gulf Central Pipeline, el oleoducto de amoníaco más largo del mundo.

⁴ La carga máxima de amoníaco por viaje depende en gran medida de la capacidad del RTC desplegado, así como de la normativa vigente en cada país, que varía considerablemente en cuanto a la longitud máxima por tren.

EE. UU. el país con la mayor infraestructura relacionada, con un total aproximado de 4.950 km. Para longitudes de hasta 5 km, los gasoductos de amoníaco son totalmente refrigerados, mientras que, para longitudes mayores, funcionan en condiciones totalmente presurizadas debido a las pérdidas de calor. El principal obstáculo para las infraestructuras de tuberías son las importantes inversiones iniciales y el largo proceso de construcción.

Foco en el almacenamiento

Las tecnologías de almacenamiento de amoníaco aplicadas, acompañadas de sus principales características técnicas, se presentan en la Tabla 0-2.

Tabla 0-2 Comparación de las tecnologías de almacenamiento de amoníaco

Método	Presión típica (bar _g)	Diseño temporal. (°C)	t _{NH3} / t _{steel} (-)	Capacidad de almacenamiento (kt) _{NH3}	Sistema de refrigeración
No refrigerado (totalmente presurizado)	16-25	20-25	2.8	<1.5	Ninguno
Semi refrigerado	3-5	0	10	0,5-2.7	Etapas únicas
Totalmente refrigerado (no presurizado)	1.2	-33	41-45	5-45	Dos etapas

El almacenamiento totalmente presurizado se realiza a temperatura ambiente y a altas presiones. Para mantener el amoníaco en estado líquido a una temperatura ambiente de 20°C, se necesita una presión de 8,58 bar_g. Sin embargo, en los recipientes de almacenamiento a presión, el amoníaco se mantiene a una presión aún mayor para garantizar que permanece en estado líquido, aunque la temperatura ambiente aumente a niveles elevados, como en entornos desérticos. Los recipientes a presión pueden ser cilíndricos, con capacidades de hasta 150 toneladas, o esféricos, con pesos que oscilan entre 250 y 1.500 toneladas. El almacenamiento presurizado es más sencillo que el refrigerado, ya que no requiere sistemas de refrigeración, y como tal, es preferible en el caso de almacenamiento móvil en caso de transporte por ferrocarril o carretera. Los tanques Nurse y los tanques ISO T50 son tipos de almacenamiento de amoníaco totalmente presurizado que se utilizan para aplicaciones agrícolas y transporte, respectivamente.

El almacenamiento de amoníaco totalmente refrigerado se realiza a bajas temperaturas y presión ambiental. Este método de almacenamiento permite la evaporación lenta del amoníaco con el paso del tiempo debido al calor transferido desde el ambiente, lo que se conoce como gas de ebullición (BOG). Por lo tanto, es necesario un sistema de refrigeración de dos etapas para conservar el amoníaco a baja temperatura y enfriarlo al entrar en la instalación de almacenamiento. Este sistema utiliza el amoníaco almacenado directamente como refrigerante en el ciclo de refrigeración. El tipo de almacenamiento totalmente refrigerado reduce significativamente el contenido de acero del recipiente, requiriendo aproximadamente 15 veces menos acero en comparación con el almacenamiento totalmente presurizado. Esto se traduce en una reducción de los costes de capital. A pesar del mayor consumo de energía asociado a la refrigeración de doble etapa, el almacenamiento totalmente refrigerado está muy extendido para el almacenamiento de amoníaco a gran escala en centros de producción y terminales de exportación e importación de amoníaco. En la actualidad, un tanque de 45.000 toneladas se considera el umbral superior para los tanques de última generación, pero es posible que se aumente en el futuro.

Por último, los tanques de amoníaco semi refrigerados pueden alcanzar capacidades de hasta 2.700 toneladas y sirven para aplicaciones de pequeña y mediana escala. Estos tanques se utilizan habitualmente en aplicaciones como barcas y fábricas. Al igual que en el almacenamiento totalmente refrigerado, el gas de evaporación (BOG) se produce a temperaturas de almacenamiento típicas cercanas a 0°C. Sin embargo,

debido a los menores requisitos de refrigeración en comparación con el almacenamiento totalmente refrigerado, una sola etapa de refrigeración es suficiente para los tanques semi refrigerados.

Foco en la seguridad

Los aspectos de seguridad del amoníaco están estrechamente relacionados con el volumen total disponible, así como con la presión y la temperatura a la que se encuentra el amoníaco en los distintos componentes de la planta. Obviamente, al considerar el almacenamiento de cualquier tipo, independientemente de si se trata de un almacenamiento móvil o estático, es aquí donde residen la mayor parte de los riesgos de seguridad. En un contexto más general, tiene sentido dividir los códigos y normas pertinentes entre los que se refieren exclusivamente a cuestiones relacionadas con la seguridad, el medio ambiente y la salud (de gestión) y los que son principalmente pertinentes para el diseño técnico y la ingeniería de las instalaciones. No obstante, existe una estrecha relación entre ambos tipos de normas, ya que la entrada y la salida se generan entre ellos. La responsabilidad de la salud y seguridad del personal y de la salud y seguridad y protección del medio ambiente y del público recae principalmente en el propietario/operador de la instalación. Las instituciones (inter)nacionales, los reguladores y los institutos del conocimiento, así como la propia industria, ofrecen orientación para cumplir estos requisitos. El medio básico pero fundamental para respaldar esta responsabilidad es el establecimiento de un Sistema de Gestión de la Seguridad.

Por otro lado, en lo que respecta a la consecución de un diseño intrínsecamente seguro, existen multitud de códigos y normas aplicables como requisitos mínimos a las fases de diseño, adquisición y construcción de las instalaciones de amoníaco, así como al funcionamiento y mantenimiento de la planta.

Conclusiones y recomendaciones

Dado que se prevé que la demanda de amoníaco aumente considerablemente, se necesitan soluciones sostenibles para satisfacerla, al tiempo que se reducen las emisiones y se minimiza el impacto medioambiental. Para llevar a cabo esta ambiciosa empresa y pasar a una cadena de valor del amoníaco ecológica, es necesario dar multitud de pasos:

1. **Gobiernos:** La regulación tiene un papel fundamental en la configuración de un futuro sostenible y de bajas emisiones. La actual ralentización en el desarrollo de proyectos de amoníaco verde puede atribuirse a la falta de un argumento comercial claro para los productores. Para los consumidores, las alternativas que emiten carbono siguen siendo más baratas que el amoníaco verde y no existe un marco que cubra la diferencia de costes. Por lo tanto, el marco general del mercado sigue siendo tal que el uso de amoníaco verde no resulta atractivo para los consumidores. Mecanismos como la subasta H2Global de Alemania para el amoníaco verde o las subastas JERA de Japón para el amoníaco bajo en carbono han proporcionado resultados tangibles para algunos proyectos. Sin embargo, se trata de cantidades limitadas. Todavía se está desarrollando una vía fiable hacia un marco que permita un mercado de amoníaco verde, lo que causa incertidumbre a los promotores de proyectos y, por tanto, no se toman decisiones de inversión. Por lo tanto, la tarea clave de los gobiernos para permitir la expansión del mercado es desarrollar un terreno de juego que ofrezca a los promotores de proyectos de amoníaco ecológico un argumento comercial claro.
2. **Investigación y desarrollo:** Las tecnologías individuales en la parte inicial de la cadena de valor del amoníaco, es decir, la electrólisis y la síntesis de amoníaco, existen desde hace décadas. Por ejemplo, la electrólisis alcalina está totalmente madura, con una TRL de 9, lo mismo que las instalaciones de ASU y de síntesis de amoníaco. La novedad se encuentra en la combinación de estas tecnologías a escala, combinando la intermitencia (RES) con procesos normalmente considerados de estado estacionario (síntesis de amoníaco). Cabe esperar que el despliegue de plantas de amoníaco verde a gran escala dé lugar a una importante curva de aprendizaje en relación con el comportamiento dinámico de los componentes del proceso y su interacción. Dado que los proyectos de amoníaco verde a gran escala son plantas pioneras, los proyectos de colaboración y las asociaciones son clave para fomentar el desarrollo necesario y la mitigación de riesgos. Por último,

la acumulación de conocimientos mediante proyectos de menor envergadura y aplicaciones descentralizadas puede allanar el camino hacia la deseada ampliación de las plantas PtX.

3. **Desarrollo de infraestructuras:** La industria del amoníaco se beneficia de su amplia infraestructura que abarca todos los aspectos de la cadena de valor, incluida la producción, el transporte, el almacenamiento y la manipulación. Con estos sólidos cimientos, el sector está bien preparado para ampliar sus infraestructuras y satisfacer la creciente demanda del futuro. No obstante, un área de interés para la industria debería ser el craqueo del amoníaco, un proceso necesario para facilitar el uso del amoníaco verde como portador de hidrógeno. Aunque varios fabricantes de equipos están investigando intensamente el craqueo de amoníaco descarbonizado, la tecnología aún no está lista para su uso comercial a gran escala y, por lo tanto, se necesitan más avances. Además, debido a la gran escala y a la naturaleza costosa de los proyectos de infraestructura, tales como las terminales de importación y exportación de amoníaco y los grandes sistemas de tuberías, se necesitarán mecanismos de financiación y apoyo públicos. Por último, en aquellos lugares donde se estén llevando a cabo múltiples proyectos de producción de amoníaco verde, debería considerarse el concepto de infraestructuras compartidas. Al compartir recursos e instalaciones, los costes pueden distribuirse entre los proyectos, haciéndolos más viables económicamente. Además, este enfoque permite obtener los beneficios de la economía de escala, logrando una mayor eficiencia y ahorro de costes.
4. **Seguridad:** El amoníaco se manipula como sustancia química desde hace más de un siglo, y esta amplia experiencia se ha traducido en un alto nivel de seguridad y eficacia técnica. De hecho, la manipulación del amoníaco ha mejorado constantemente en términos de seguridad. Los avances tecnológicos han mejorado las capacidades de medición e inspección, mientras que las lecciones aprendidas se han aplicado para llevar a la industria a su estado actual. Sin embargo, el amoníaco, al igual que otros combustibles descarbonizados como el metanol y el hidrógeno, al ser menos conocidos por la población, podrían considerarse más peligrosos. Esto también es evidente en el enfoque cauteloso adoptado por algunos puertos de importación/exportación a la hora de desarrollar infraestructuras para el amoníaco, derivado de preocupaciones medioambientales y de seguridad.
5. **Sistemas de certificación:** Estos sistemas desempeñan un papel crucial en el desarrollo de combustibles descarbonizados, incluido el amoníaco verde. Muchos países, ya actúen como exportadores o como importadores, trabajan activamente en el establecimiento de marcos de certificación que garanticen la igualdad de condiciones para todas las partes implicadas. Estos esquemas proporcionan pruebas de que se siguen metodologías y marcos analíticos específicos de acuerdo con normas y requisitos definidos. Como resultado, se establecen la credibilidad y la transparencia, y los consumidores pueden estar seguros de que un producto o servicio certificado cumple sus expectativas. Por supuesto, es necesaria la armonización y el reconocimiento mutuo de estos sistemas para permitir el libre flujo de combustibles descarbonizados a través de las fronteras y evitar las barreras de mercado que obstaculizan el comercio del amoníaco.
6. **Colaboración internacional:** La colaboración entre proveedores de tecnología, industrias e instituciones de investigación es crucial para compartir conocimientos, aplicar las mejores prácticas e impulsar la adopción generalizada de tecnologías verdes de amoníaco en todo el mundo. Dada la naturaleza de este mercado emergente, es esencial que tanto los países importadores como los exportadores formen asociaciones internacionales que faciliten el comercio.

Abbreviations

Name	Explanation
AEA	Ammonia Energy Association
AEL	Alkaline Electrolysis
AEM	Anion Exchange Membrane
API	Active Pharmaceutical Ingredient
ASU	Air Separation Unit
BAT	Best Available Technologies
BESS	Battery Energy Storage System
BFD	Block Flow Diagram
BL	Battery Limit
BRZO	Besluit Risico Zware Ongevallen
Capex	Capital Expenditures
CFC	Chlorofluorocarbon
COP	Conference of Parties
CRI	Commercial Readiness Index
DWDI	Double Wall Double Integrity
EFMA	European Fertilizer Manufacturers Association
EP	Engineering and Procurement
EPC	Engineering Procurement and Construction
ERC	Emergency Release Coupler
ESD	Emergency Shut Down
FID	Final Investment Decision
GHG	Greenhouse Gas
GWP	Global Warming Potential
HAZOP	Hazard Operability
HB	Haber Bosch
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HTS	High Temperature Shift
ICE	Internal Combustion Engines
IEA	International Energy Association
IFA	International Fertilizer Association
IFS	International Fertilizer Society
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization:
KSA	Kingdom of Saudi Arabia
kt	Kilotonne
LCOA	Levelized Cost of Ammonia
LCOAT	Levelized Cost of Ammonia Transport
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LOPA	Layers of Protection Analysis

Name	Explanation
LPG	Liquified Petroleum Gas
MAPCO	MidAmerica Pipeline System
MAPP	Major-Accident Prevention Policy (
MPA	the Maritime and Port Authority of Singapore
Mt	Megatonne
Mtpa	Megatonne per annum
MTPD	Metric Tonne per Day
NAR	Non-accidental release
NGHC	NEOM Green Hydrogen Company
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
Opex	Operational Expenditures
OSHA	Occupational Safety and Health Administration
PEM	Proton Exchange Membrane
POD	Port of Discharge
POL	Port of Loading
PSA	Pressure Swing-Adsorption
PV	Photovoltaic
QRA	Quantitative Risk Assessment
RE	Renewable
RID	Regulation concerning the International Carriage of Dangerous Goods by Rail
RTC	Rail Tank Car
SAICM	Strategic Approach to International Chemicals Management
SCC	Stress Corrosion Cracking
SCR	Selective Catalytic Reduction
SIL	Safety Integrity Level
SMR	Steam Methane Reforming
SMS	Safety Management System
SO	Solid Oxide
TIC	Total Installed Cost
TRL	Technical Readiness Level
UN	United Nations
USA	United States of America

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1 Introduction

1.1 Project Idea and Strategic Benefits

Ammonia (NH₃), a globally traded commodity, has the potential to play a significant role in reducing greenhouse gas emissions. As the world strives to limit global warming to well below 2 °C, ammonia production can be transformed to become more environmentally friendly. With its production reaching approximately 186 Mt in 2020 (IFA, 2024), the adoption of green ammonia (NH₃) could have a substantial impact on reducing carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), and fluorinated gases. This shift towards greener ammonia production aligns with the international treaty on climate change established during the 21st United Nations Conference of the Parties (COP21) in Paris in 2015, which aims to combat global warming and its detrimental effects.

Chile possesses immense renewable energy potential, making it a prime candidate to become a major exporter of green ammonia on a global scale. The Atacama Desert, located in the northern region of Chile, is renowned for its exceptional solar capacity factor of up to 35% and solar irradiance of 275 – 300 W/m². In the south, the Magallanes region presents wind capacity factors in the range of 70%. Leveraging such potential, Chile has the opportunity to establish itself as one of the leading exporters of green ammonia internationally. Towards this goal, various development efforts are taking place in the whole country (Rouwenhorst, 2023).

1.2 Scope of the Project

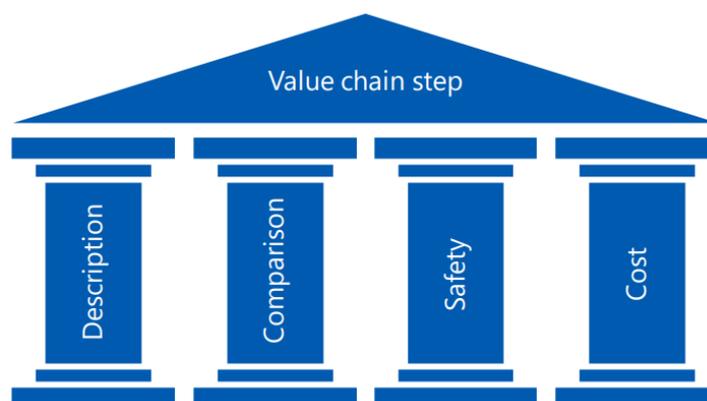
The primary aim of this report is to offer technical support in gathering information on topics that have not been extensively explored or where public information is not readily accessible. With various projects involving the production of green ammonia planned in Chile, it is essential to gain a deeper understanding of the existing international ammonia installations, with a specific focus on safety-related aspects and prevention measures. Consequently, the main objective of this report is to provide a comprehensive depiction of the cutting-edge ammonia installations currently operational.

Therefore, the following four Study Objectives (SO) scope will be covered:

- SO1: General overview of the green ammonia value chain
- SO2: Ammonia production
- SO3: Ammonia transport
- SO4: Ammonia storage and handling

As reflected in Figure 1-1, for SO2-4 a standard common structure was adopted for each block of the ammonia value chain to enable a better orientation for the reader.

Figure 1-1 Standard structure with four main topics for SO2



1.3 Report Structure

The overall structure of the current report is as follows:

Section 2, provides an overview of the ammonia value chain as well as presents the four countries that are going to be on the focus in the current study.

- Section 3, describes and compares well established ammonia production licensors including Topsoe, Casale, KBR , Thyssenkrupp and Stamicarbon.
- Section 4, describes various methods of transporting ammonia including pipelines, rails, ships, barges and trucks. Additionally, insights into the safety aspects of these methods are given and the calculation of the Levelized Cost of Ammonia Transport (LCOAT) for various scenarios is conducted.
- Section 5, describes and compares the state of the art of ammonia storage. A comparison of costs is conducted, and safety precautions and regulations are presented.
- Section 6, presents the outlook and recommendations of the executed investigation.
- Section 7, includes the annexes of the report.
- Section 8, summarizes the bibliography used for the development of the study.

2 SO1 - General Overview of the Green Ammonia Value Chain

Current Status

The production of ammonia has grown steadily over the years, reaching approximately 186 Mt in 2020 (IFA, 2024).

Figure 2-1 Global production of ammonia between 2011-2020.

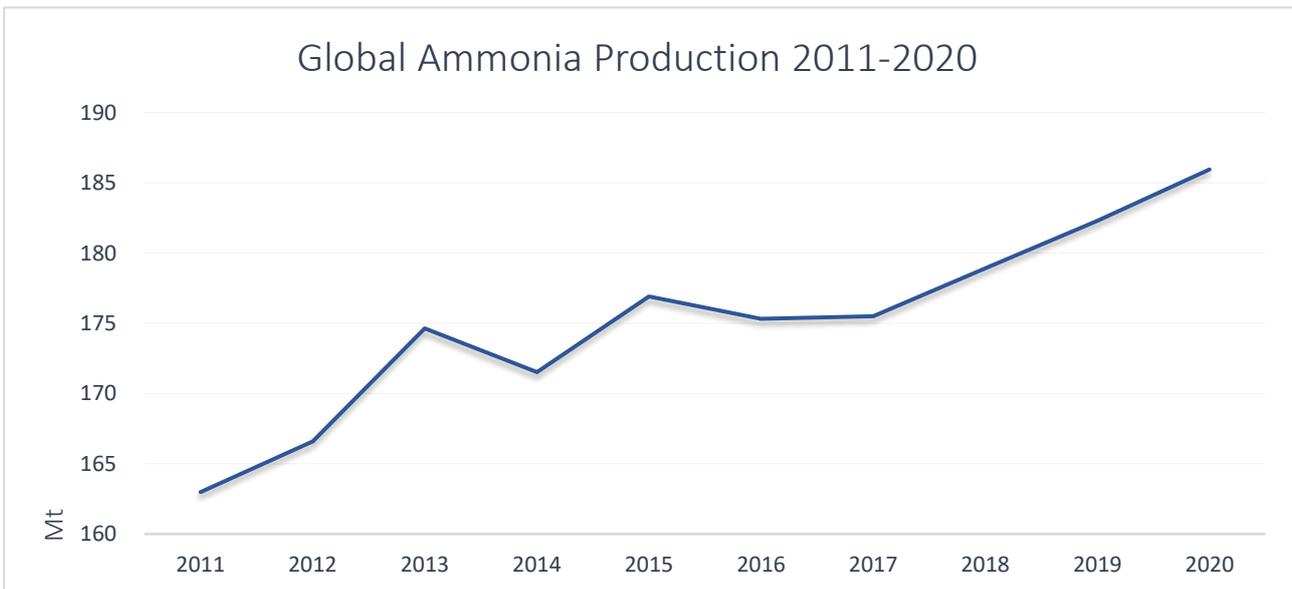
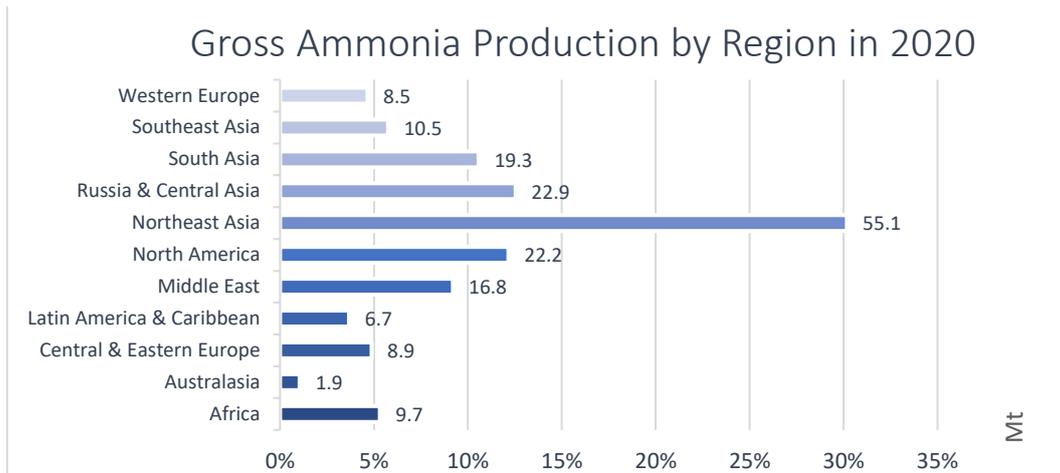


Figure 2-2 Gross ammonia production by Region in 2020



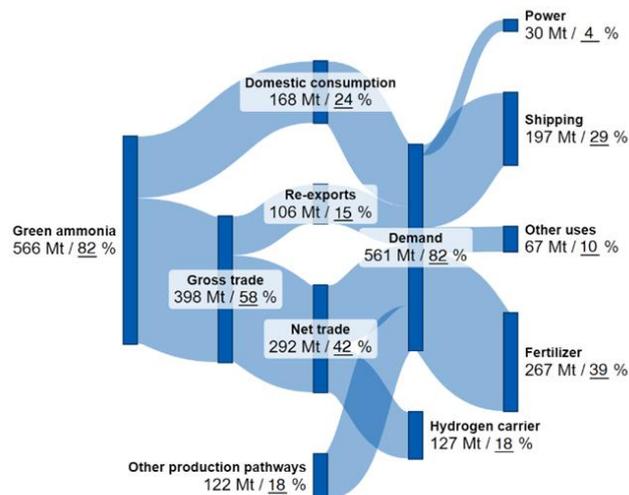
More than 50% of this ammonia was produced in Asia and Russia. North America had also a substantial share, accounting for 12% of the worldwide production, while being followed by Middle East with 9%. A detailed overview can be gained via Figure 2-2 (Hatfield, 2020).

Nearly all this ammonia is generated from fossil fuels: natural gas (72%), coal (22%), naphtha (4%), heavy fuel oil (2%), while the rest (1%) is derived from other feedstocks. As a result, the ammonia life-cycle emissions amount to 0.5 Gt of carbon dioxide (CO₂), or 1% of global emissions, making ammonia the largest emitter in the chemical industry (Breiki, 2021) (Zhou, 2010).

Future Potential

In the coming years, the increasing population and rising affluence worldwide will drive the need for more ammonia. However, this surge in demand coincides with governments worldwide committing to achieving net-zero emissions in the energy sector. Therefore, there is mounting pressure to find sustainable solutions that meet the growing ammonia demand, while minimizing environmental impact. As such, the current study will focus exclusively on the green ammonia. According to IRENA’s 1.5°C scenario, considering optimistic capital expenditure assumptions, the annual green ammonia production is projected to be 566 Mt in 2050 (IRENA, 2022).⁵ The expected energy flows are detailed in Figure 2-3, which highlights the potential for ammonia expansion into new end-uses.

Figure 2-3 Green ammonia production projection in 2050 based on IRENA’s 1.5°C scenario.



⁵ In addition to the 566 Mt of annual green ammonia production, 122 Mt of ammonia being produced via low carbon pathways is projected.

It is evident that hydrogen and its derivatives such as ammonia are promising energy carriers that can play a crucial role in the transition to a low-carbon future. To quantify their greenhouse gas (GHG) emissions, the International Energy Agency (IEA) and most proposed regulations /certification systems follow a methodology that assigns zero emissions to renewable electricity use and excludes emissions from equipment manufacturing (IEA, 2023). However, from a life-cycle perspective, hydrogen production emissions are far from zero. Hydrogen production emissions are influenced by several factors, including the involved technologies (e.g., RE electricity production, type of electrolyzers & ammonia synthesis technology) as well as the overall system's configuration (i.e., export and/or supply of electricity from /to the grid). Typically, the largest contributor to hydrogen production emissions is the electricity production to power the electrolyzer. Regarding RE electricity generation technologies, solar photovoltaics (PVs) are associated with higher life cycle GHG emissions compared to wind plants. This is attributed to the manufacturing process of solar panels, which tends to have higher emissions compared to the production of wind turbines (Reuß, 2019) (Sternberg & Bardow, 2015).

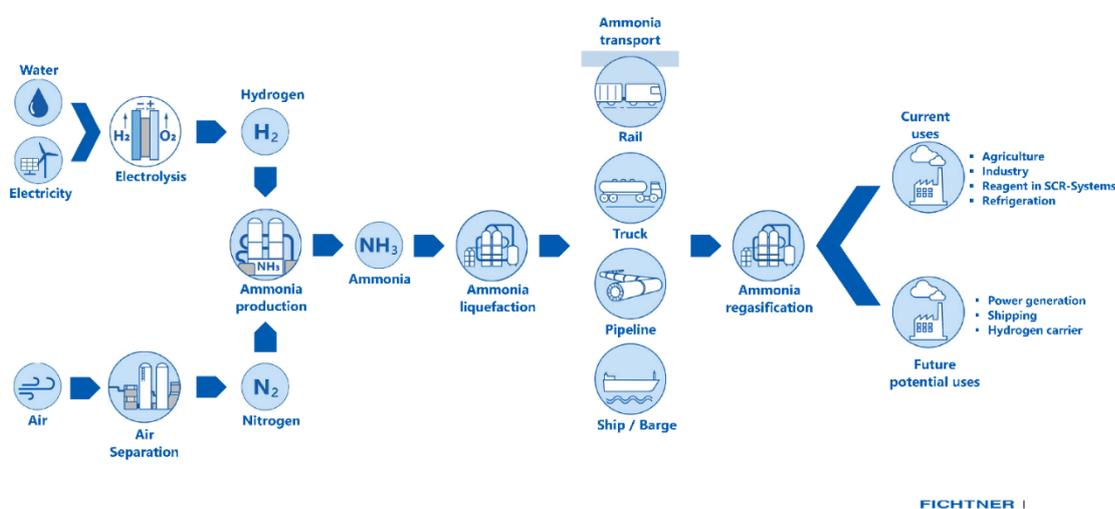
According to a recent study by Kiane, which considers such a life cycle calculation approach, the GHG emissions associated with green hydrogen production show a wide range of the emitted kgCO_{2e} per kgH_2 across 1,025 worldwide planned projects⁶. The most favorable results were achieved when considering a configuration, in which the renewable plant has double the capacity of the electrolysis plant and can export excess electricity back to the grid. In this scenario, the median production emissions are reduced to some 2.9 kgCO_{2e} per kgH_2 . Furthermore, conversion of hydrogen to ammonia and shipping over a 500–20,000 km distance, with reconversion ('cracking') to hydrogen at the destination points, has emissions in the range of 4.2–6.1 kgCO_{2e} per kgH_2 . Delving deeper, hydrogen to ammonia emits 1.8 kgCO_{2e} per kgH_2 and cracking to recover hydrogen emits 0.3 kgCO_{2e} per kgH_2 (Kiane, 2024).

Considering the above, it becomes apparent that green hydrogen and its derivatives, can be associated with significant emissions throughout their entire life cycle. To fully capitalize on the environmental benefits, they offer, it is crucial that the complete value chain is optimally designed, starting from the early stages of any project (i.e., pre-feasibility stage).

2.1 Ammonia Value Chain

The green ammonia value chain is presented in Figure 2-4 and explained in the following sections.

Figure 2-4 The green ammonia value chain

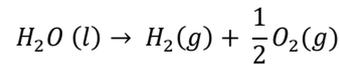


⁶ Including green hydrogen facilities planned in 2020, covering different electrolyzer technologies and electricity sources in 72 countries.

2.1.1 Upstream

Hydrogen Production

The structure of the green NH₃ value chain begins with the supply of H₂. It can be differentiated between the conventional fossil and renewable methods for H₂ production. With the goal of achieving a CO₂ free energy system, the focus is only on decarbonized H₂. In this context, electrolyzers are deployed, which produce carbon free H₂ through water and electricity from renewable energy sources. The overall chemical reaction follows the equation:



The following four technologies with different electrolytes⁷ are currently commercially available (IEA):

- Alkaline Electrolysis (AEL): The alkaline electrolysis has metal electrodes that are surrounded by an alkaline liquid medium. The cells are separated by a permeable membrane. AEL electrolysis has been used for more than 120 years for industrial hydrogen production and is considered to have a Technical Readiness Level (TRL) of 9 with various suppliers that can provide MW-modules.⁸
- Polymer Electrolyte Membrane (PEM) electrolysis: Contrary to alkaline electrolysis, this process works in an acidic environment, which makes it necessary to use precious metals as electrodes to prevent corrosion. The development of PEM electrolysis started in the 1960s. After 20 years of development for military and aerospace, R&D activities led to the first commercial application in the beginning of 2000 with further R&D reaching the status of modern PEM systems available at the market. PEM is considered to have a TRL of 8-9 with various suppliers, that can provide MW-modules.
- Solid Oxide (SO) electrolysis: SO-Electrolysis works at high temperatures. A part of the necessary decomposition energy is drawn from external heat (ideally external waste heat), which reduces the electricity demand. The first development took place in the late 1960s, with new interest and increased R&D activities in the last ten years leading to the first commercially available systems currently from only a few suppliers. SO-electrolysis is considered to have a TRL of 6 with only a few suppliers that can provide kW-modules.
- Anion Exchange Membrane (AEM) electrolysis: AEM electrolyzers try to combine the advantages of AEL and PEM electrolyzers by being basically designed comparable to a PEM electrolyzer, but using an alkaline electrolyte (as in an AEL electrolysis) and a semi-permeable membrane to conduct OH⁻ anions. Overall, this design aims to reduce the need for rare metals (especially iridium) and thus lower investment costs, with similar efficiencies and comparably dynamic operating ranges. AEL is considered to have a TRL of 5 with only one supplier that can provide kW-modules and multiple suppliers that are developing the first products.

For completeness, it shall also be stated, that biomass-based hydrogen production is an alternative to the electrolysis-based hydrogen production. However, it is restricted in small-scale ammonia synthesis applications. The biomass-hydrogen production alternatives are classified into thermochemical, including pyrolysis and gasification, as well as in biochemical, including anaerobic digestion and fermentation (Elishav, Mosevitzky, Medina, & Grader, 2021). In general, the technical potential of biomass to satisfy the demand for hydrogen is orders of magnitude smaller than that of renewable energy sources, due to the limited availability of biomass (IEA, 2019).

Nitrogen Production

The second fundamental element to produce ammonia is nitrogen N₂. In 2021, 152 Mt of nitrogen were used mostly within the fertilizer industry (71%), with a split in urea-based fertilizers (47%) and non-urea-based fertilizers (24%). The remaining 29% was used in non-fertilizer industries (IEA, October 2021). Nitrogen is

⁷ The electrolyte is the media responsible for transporting the generated chemical charges (anions or cations) from one electrode to the other. In technical applications, a membrane between the electrodes prevents the products formed at the electrode from mixing.

⁸ The definition of the TRL is given in Section 7.2.

taken out of the air, as its share is >75% by weight. Its local production can be divided in mainly three technologies:

- Pressure Swing-Adsorption (PSA): A pressure swing-adsorption separates single gases (in this case N₂) from a gas composition (air) by using different molecular characteristics and affinities for different adsorbent materials. PSA units are used for multiple purposes in the chemical business (e.g., nitrogen production, hydrogen drying, hydrogen purification, oxygen production, polypropylene purification) consisting different adsorber materials and different numbers of adsorber beds. PSA units have been used for multiple centuries with thousands of currently operated plants.
- Air Separation Unit (ASU): A (cryogenic) air separation unit separates the different parts of air (78% N₂, 21% O₂, 0.9% Ar, 0.04% CO₂) by their different dew point. Therefore, the air is compressed and cooled down to cryogenic temperature and then sent to a distillation column where the O₂ and N₂ are separated. ASUs have been developed in the early 1900s and continuously developed to achieve higher efficiencies and gas qualities.
- Membrane systems: A membrane nitrogen generation unit uses the rather simple concept of membrane permeation to separate nitrogen from the other gases. Air is fed through polymer fibers and due to the fact that the permeation factor of CO₂, O₂, H₂O, Ar is higher than the permeation factor of N₂, nitrogen sustains in the fiber, while the other gases are released through the shell.

For very large-scale ammonia plants (over 2500 t/day) ASU's are deployed, for their high nitrogen production capacities, reaching up to 270,000 Nm³/h and the ability to achieve nitrogen qualities (concerning noble gases like Argon and oxygen containing components) up to parts per billion (ppb). Nowadays, this is applicable to only a few ammonia plants worldwide, as it concerns only large scale and quite modern facilities. Quite commonly, normal air is introduced in the process to serve as an oxidizer in the combustion of the heating fuel. The nitrogen produced during combustion is used subsequently as the feedstock in the ammonia synthesis.

Ammonia Synthesis

Based on the fundamental research work of Fritz Haber, Carl Bosch together with his engineering team developed the ammonia synthesis to technical operability using the promoted iron-based catalyst found by Alwin Mittasch and his co-workers. Since then, although process technology has been improved over the years, there have been no fundamental changes in the chemical reaction itself (IFA, 1997).

The elemental nitrogen and hydrogen react by the presence of an iron-based catalyst, following the equation:



Ammonia synthesis is an exothermic reaction that occurs naturally at low temperatures. However, the reaction rate at room temperature is insufficient for industrial-scale applications. To achieve the desired conversion rate, the reaction requires high pressure, high temperature, and the use of a catalyst to enhance the reaction kinetics. Industrial reactor conditions for ammonia synthesis typically involve temperatures ranging from 350-550°C and pressures ranging from 100-460 bar. These conditions are necessary due to the limited activity of iron-based catalysts commonly used in industry and still the most favourable as opposed to natural nitrification processes and the strong nitrogen-nitrogen bond in atmospheric nitrogen. The conversion is strongly related to the thermodynamic equilibrium governing the reaction. Hence one cannot reach 100% conversion in one cycle. Notably, achieving near-complete conversion to ammonia under industrial conversion conditions is not feasible. As a result, significant recycling is required in commercial ammonia synthesis processes. The synthesized ammonia is condensed using water (once-through or via cooling towers system), air or a combination of air and water as a cooling medium⁹. It is then separated from the reaction loop through a series of liquid/vapor separations, which are operated at different pressures. Typically, each pass through the reactor converts around 15-28% of the nitrogen to ammonia, depending on the set-up of the ammonia synthesis loop. The ammonia is then depressurized, and the resulting flash gases, mainly nitrogen and hydrogen, are sent

⁹ Air cooling is mostly deployed at locations with water scarcity.

back to the compressor unit for recycling. The gaseous ammonia is directed to the refrigeration system of the plant for further processing, while the liquid ammonia is sent to the storage tank.

Today, the Haber-Bosch (HB) technology is still the primary method for ammonia synthesis. The existing HB alternatives as well as future synthesis potentials being currently under investigation are described in Section 2.6.1.

2.1.2 Midstream

Ammonia has been handled in large quantities for several decades, and as a result there is already a high maturity of storage, transport, and distribution technologies. Ammonia is a gas at ambient conditions. However, being relatively easily liquefied, it is always transported as a liquid.

After synthesis, various modes of transportation are utilized to transport it to its intended destinations. Ships play the most significant role in ammonia transport, especially for long-distance shipments across oceans. Specialized ammonia tankers are designed to safely carry large quantities of ammonia in liquid form. Annually, 18-20 Mt of ammonia are transported by ship, with around 170 ships being in operation that can carry ammonia, of which 40 carry ammonia on a continuous basis (Brown, 2019) (Hatfield, 2020). Barges are also used for transporting ammonia, particularly for inland waterways and river systems.

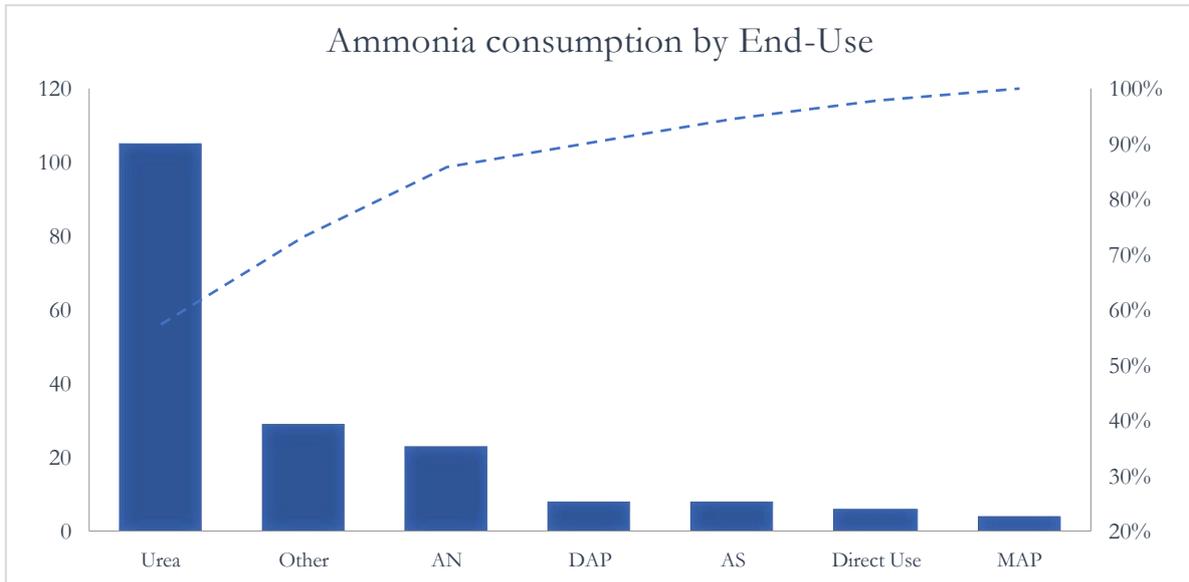
For onshore transport, pipelines provide a reliable and efficient means of transporting large quantities of ammonia continuously, connecting production facilities to distribution centres or directly end-users. Ammonia pipelines are a well-established technology with approximately 4,950 km only in the USA that can transport around 2 Mtpa. For shorter distances and intermittent supply requirements, trucks and rail transport are employed that transport ammonia as pressurized liquid within storage vessels (Barbers, 2008).

Storage is needed at various stages of the ammonia value chain to act as a buffer between supply and demand. At ammonia synthesis plants, storage tanks hold the produced ammonia before it is transported to distribution centres or end-user. At ports, either acting as import or export terminals, storage is necessary to enable efficient handling, by coordinating the logistics and ensuring that ammonia is readily available for distribution even if there are disruptions in production or delays in shipping schedules. Lastly, end-user facilities that utilize ammonia, have on-site storage tanks to store ammonia for their specific needs.

2.1.3 Downstream

2.1.3.1 Current Ammonia Uses

Figure 2-5 Ammonia consumption by end-use in 2020



Currently, approximately 85% of ammonia production is dedicated to the manufacturing of synthetic nitrogen fertilizers. However, it is important to note that ammonia has a diverse range of other applications, including refrigeration, mining, pharmaceuticals, water treatment, plastics and fibers, as well as the abatement of nitrogen oxides (NO_x). The distribution of ammonia consumption across various end-uses is presented in Figure 2-5¹⁰, highlighting indeed the dominance of fertilizer use (Hatfield, 2020).

Agriculture

The utilization of ammonia in the fertilizer industry originated in the 1920s after the expansion of the Haber-Bosch synthesis process at commercial scale. Currently, ammonia is a vital component in fertilizers enhancing crop productivity internationally. Serving as a crucial nitrogen source, ammonia supplies essential nutrients for plant growth and development, making fertilizers derived from ammonia indispensable in modern agriculture. Table 2-1 presents an overview of the nitrogen fertilisers production in 2020, highlighting the fundamental role of ammonia as the primary building block of those (IEA, 2021).

Table 2-1 Nitrogen fertilisers production in 2020 and their precursors

Product	N ₂ (w/w)	Precursors	Global production (Mt)
Ammonia - NH₃	82%	H ₂ , N ₂	183
Urea - H₂NCONH₂	46%	NH ₃ , CO ₂	177
Ammonium nitrate - NH₄NO₃	34%	HNO ₃ , NH ₃	49
Calcium ammonium nitrate - 5Ca(NO₃)₂NH₄NO₃	27%	CaCO ₃ , NH ₄ NO ₃ , H ₂ O	14

¹⁰ AN: Ammonium Nitrate, DAP: Diammonium Phosphate, AS: Ammonium Sulphate, MAP: Monoammonium Phosphate

Product	N ₂ (w/w)	Precursors	Global production (Mt)
Urea ammonium nitrate - CH ₆ N ₄ O ₄	30%	NH ₄ NO ₃ , CH ₄ N ₂ O, H ₂ O	25
Diammonium phosphate - (NH ₄) ₂ HPO ₄	18%	NH ₃ , H ₃ PO ₄	9
Monoammonium phosphate - (NH ₄)H ₂ PO ₄	11%	NH ₃ , H ₃ PO ₄	7
Ammonium sulphate - (NH ₄) ₂ SO ₄	21%	NH ₃ , H ₂ SO ₄	12
Nitric Acid - HNO ₃	13%	NH ₃ , O ₂	Non disclosed

In general, there is no universal approach to farmers' selection of mineral fertiliser product. Multiple factors influence the decision in each context, including among other weather conditions, soil types and crop types. As such, nitrogen fertilizer application by end-product varies significantly across the globe.

Industry

Ammonia is used across various industries. Some examples include the following (Sharma, 2023) (ARAX CHEMISTRY, 2023):

- In chemical industry, several compounds use ammonia as its production basis. Some examples include amines, nitriles, hydrogen cyanide, hydrazine hydroxylamine, amino acids, acrylonitrile, caprolactam, melamine, MDI, TDI, nitrobenzene and phenol. As such, ammonia contributes to the production of various end-products, such as plastics, nylons, fabrics, pesticides and dyes.
- In the mining industry, ammonia is employed in the extraction and purification of metals like copper and nickel. It is used as a leaching agent to dissolve these metals from ores, facilitating their separation and purification. This process is known as ammoniacal leaching.
- In petroleum industry, ammonia is being utilized to neutralize the acid constituents of crude oil and to protect equipment against corrosion.
- In the fermentation industry, ammonia solutions that act as the sources of nitrogen for microorganisms are used. Those also adjust the pH during the fermentation process.
- In the pharmaceutical industry, ammonia is used in the manufacture of API's (Active Pharmaceutical Ingredient) and drugs which inhibit the growth and multiplication of certain types of bacteria.
- In the explosion industry, the ammonium nitrate, an ammonia product, is used as the major compound for making explosives.
- In water treatment industry, ammonia is commonly used to neutralize acids and control pH levels.

Reagent in SCR Systems

Selective Catalytic Reduction (SCR) has been applied to stationary source fossil fuel-fired combustion units for emission control since the early 1970s and is currently being used worldwide to reduce the nitrogen oxide emissions. A nitrogen-based reducing agent (reagent), such as ammonia or urea-derived ammonia, is injected into the post-combustion flue gas. The reagent reacts selectively with the flue gas nitrogen oxides within a specific temperature range and in the presence of the catalyst and oxygen to reduce the NO_x into molecular nitrogen and water vapor.

Results of a survey of electric utilities that operate SCR systems indicated that about 80 percent use ammonia (anhydrous and aqueous), and the remainder use urea (John L. Sorrels, 2019).

Ammonia in Refrigeration (R717)

Ammonia was first used as a refrigerant around 1850, when the compression refrigeration cycle was invented. Common household ammonia is typically a mixture of approximately 10% ammonia by weight diluted with water, whereas the ammonia used in refrigeration installations is known as anhydrous ammonia, as it contains very little water (99.8% pure ammonia). Ammonia has a high latent heat of vaporization, enabling it to absorb a significant amount of heat during its liquid-to-gas phase transition. For example, ammonia can remove almost six times as much heat per pound as R410a, a synthetic refrigerant alternative (Basset Mechanical, 2024). This reduces the amount of ammonia that must be circulated in a refrigeration system, leading to smaller piping size and lower compressor energy consumption. As such, due to its high energy efficiency, ammonia is an ideal refrigerant for large commercial and industrial refrigeration systems.¹¹ Currently, less than 2 percent of all the ammonia commercially produced in the world is used as a refrigerant. However, with chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) based refrigerants being phased out from the Montreal Protocol as well as increased regulation being placed upon hydrofluorocarbon (HFC) based refrigerants, alternative refrigerants for use in existing refrigeration systems are actively being investigated (ASHRAE, 2017). In this context, Ammonia, being a naturally occurring substance and having both an Ozone Depletion Potential (ODP) rating of 0 as well as a Global Warming Potential (GWP) rating of 0, is expected to increase its share in the refrigerants market in the upcoming years.

2.1.3.2 Potential Future Ammonia Uses

In addition to the existing applications, intensive research is currently being conducted on new potential uses for ammonia. The most significant ones include ammonia for power generation, ammonia for shipping, and ammonia as a hydrogen carrier. Collectively, these fields are projected to create a demand of 354 Mt of ammonia by 2050 (refer to Figure 2-3).

Ammonia for Power Generation

Ammonia can potentially be used as a fuel for power generation in gas turbines or furnaces, displacing natural gas or coal.

In Japan, the co-firing of ammonia with coal is part of the national roadmap for establishing a fuel ammonia supply chain. In June 2024, Jera, the largest power generation company in the country, concluded an ammonia co-firing trial at a coal power station with positive results. Specifically, 20% of ammonia was co-fired at a 1-gigawatt (GW) coal plant, being the world's first trial using such a large amount of the gas at a commercial plant. The results were positive, confirming that nitrogen oxides (NO_x) levels were no higher than when firing coal alone, sulphur oxides (SO_x) were reduced by 20%, and generation of nitrous oxide (N₂O), which has a strong greenhouse effect, was below the detection threshold (Yuka Obayashi, 2024). Noteworthy to mention, that the costs of CO₂ mitigation can be low, but this relies on a low-cost supply of ammonia. However, attention needs to be paid to NO_x emissions, as additional treatment may be required to address this issue. To conclude, co-firing coal with ammonia can only be a transitional measure, as there are still significant CO₂ emissions remaining (IEA, 2019).

Ammonia is another potential fuel for gas turbines (IEA, 2019). The direct use of ammonia has been successfully demonstrated in micro gas turbines with a power capacity of up to 300 kW (Arai, 2020). Additionally, IHI Corporation demonstrated that a simple cycle gas turbine of 2MW capacity, the IM270, was found to be stable across the entire range of ammonia mixing ratios with natural gas (up to 100%), while co-firing would reduce CO₂ emissions in proportion with the co-firing rate. Furthermore, it has been confirmed that the NO_x removal device can effectively reduce NO_x concentration to below 7 ppm, while unabated NO_x emissions lie to around 280 ppm (Ito, Uchida, & Suda, 2019). Efforts are currently being made also for larger

¹¹ An example of a design standard for ammonia refrigeration applications is "PGS 13 - Ammonia as a refrigerant in cooling systems and heat pumps", a Dutch Guideline for safe use of ammonia as a refrigerant in refrigeration systems and heat pumps, applicable when more than 10 kg of ammonia refrigerant are deployed

scale turbines, with Mitsubishi Power commencing development of the first ammonia fired 40 MW Class Gas Turbine System (Mitsubishi Power, 2021).

Ammonia for Shipping

Ammonia was first used as a fuel a long time ago. Due to a shortage of diesel during World War II, Belgium had to find an alternative fuel for its public buses. In 1943, Ammonia Casale introduced an internal combustion engine that could run on a blend of ammonia and coal gas. Around 100 buses in Belgium used this system, known as Gazamo, until diesel supplies became available again (Galluci, 2021).

In 2018, according to the International Maritime Organization (IMO), the GHG emissions expressed in CO_{2e}, were equal to 1,076 million tonnes contributing to 2.89% of the global anthropogenic emissions (IMO, 2021). The 2023 strategy of the IMO aims to be net zero by or around 2050. Therefore, shipping companies seek climate-friendlier alternatives to replace heavy fuel oil and LNG towards cutting down their emissions. Due to the long distances involved in international shipping, direct electrification is not feasible. On the other hand, ammonia, with the capability to power vessels for extended periods at sea while still allowing space for cargo (due to its high energy density), is acknowledged as a quite attractive alternative marine fuel (IRENA & AEM, 2022).

Although ammonia is not currently commercially used as a fuel for oceangoing ships, extensive research is being conducted to demonstrate its compatibility as a combustion fuel in internal combustion engines (ICEs). Several consortiums are formed, and the research showcases that there are no major obstacles anticipated in using ammonia as a fuel. However, it is important to address the significant challenges of ammonia related to its toxicity and associated risks. While these challenges can be managed, they will introduce complexity to ship designs. Furthermore, ICEs that combust ammonia are expected to require after treatment technologies, such as SCR, to control NH₃ slip as well as additional catalysis to control N₂O emissions, both of which are already available technologies (European Maritime Safety Agency, 2023). In March 2024, Fortescue, in collaboration with the Maritime and Port Authority of Singapore (MPA), government agencies, research institutes, and industry partners, has achieved a significant milestone by successfully utilizing ammonia as a marine fuel. This groundbreaking trial took place on the Fortescue Green Pioneer, a Singapore-flagged vessel, in the Port of Singapore. The ship was loaded with liquid ammonia from an existing facility for the purpose of testing the fuel and co-fired with diesel (MPA Singapore, Fortescue, 2024). Further notable developments include Wärtsilä launching the shipping industry's first commercial 4-stroke ammonia engine, while engine manufacturer MAN Energy Solutions announced to have commercially available ammonia engines in 2027. (Tan, 2024) (Wärtsilä, 2024).

In addition to conventional engine technologies, Solid Oxide Fuel Cells¹² (SOFCs) are considered. By electrochemically converting fuel into electricity, SOFCs can potentially produce power with higher efficiency than internal combustion engines running on the same fuel-without creating polluting emissions or particulates. (Blenkey, 2021).

According to IRENA the ammonia demand for shipping in 2050 would be in the range of 197 Mt (refer to Figure 2-3). However, this may prove to be a too conservative estimate.

Ammonia as Hydrogen Carrier

Ammonia is commonly proposed as a hydrogen carrier¹³ to overcome the storage and transport challenges of hydrogen.

¹² A fuel cell is a device that converts chemical energy from a fuel into electricity through an electrochemical reaction of the fuel with oxygen or another oxidising agent.

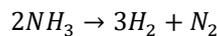
¹³ A carrier is defined as a material, other than the H₂ molecule, that can be used to transport hydrogen.

Table 2-2 Ammonia and Hydrogen Properties

Properties	Units	H ₂	NH ₃ - Fully Pressurized	NH ₃ - Fully refrigerated
Phase ¹⁴		liquid	liquid	liquid
Boiling Point (at 1bar _g)	°C	-253	-33	
Density	kg/m ³	70.8	610	680
Volumetric H ₂ Content	kg _{H2} /m ³	70.8	107.7	120
Volumetric Energy Density	MJ/L	8.49	12.92	14.4

In Table 0-1Table 2-2, a comparison of some selected properties of the two mediums justifies why (Sudipta Chatterjee, 2021).

Firstly, ammonia has an essentially higher boiling point at ambient pressure in comparison with the extremely low - 253°C of hydrogen, being easily liquified for transportation and handling. After liquefaction, either as fully pressurized or fully refrigerated, ammonia contains higher mass of hydrogen per volume, i.e. is able to transport a larger mass of hydrogen to its consumption destination for the same transport volume. In addition to the aforementioned characteristics, ammonia is a one-way carrier. This means that it can be decomposed at a distribution site to produce hydrogen, and the resulting byproduct (nitrogen), is environmentally friendly and holds no value. On the other hand, two-way carriers, such as LiBH₄, need to be transported to a distribution site in a "hydrogenated" form, dehydrogenated to release hydrogen, and then the dehydrogenated material must be returned to a processing site where it can be re-hydrogenated for reuse. Avoidance of the post-processing simplifies the overall cracking cycle giving ammonia a competitive advantage (Sudipta Chatterjee, 2021). The ammonia's decomposition (i.e. cracking) to its elemental substances, hydrogen and nitrogen, follows the equation:



At the time of writing this report, various OEMs are conducting research concerning ammonia cracking. However, the technology is not yet ready for intensive decarbonized large-scale commercial use¹⁵. Table 2-3 provides an exemplary overview of available OEMs, without the claim of completeness as well as including any kind of recommendation.

Table 2-3: Ammonia cracking OEMs

Scale	Original Equipment Manufacturer
Large	<ul style="list-style-type: none"> • Topsoe • ThyssenKrupp • Johnson Mattheys
Small	<ul style="list-style-type: none"> • Amogy (n/a) • Lindberg (275 kg/day) • Metacon (n/a) • Proton Ventures (n/a) • Starfire Energy (0.5 t/day or 480 kg/day) • CI Hayer (136-228 kg/day) • Koyo Thermo (96 kg/day) • Borel (11 kg/day)

¹⁴ Properties presented for liquid H₂ at -253 °C & 1 bar_g, for fully refrigerated NH₃ at -33°C & 1bar_g and for fully pressurized NH₃ at 20°C & 10 bar_g.

¹⁵ Large scale ammonia cracking with the use of fossil fuels is a mature technology.

Table 2-4 presents potential ammonia cracking technologies and their TRL (Rouwenhorst, Van Der Ham, Mul, & Kersten, 2019). The ammonia cracking reaction is endothermic, and the temperature required for efficient cracking depends on the catalyst being used. There are a wide variety of materials that have been found to be effective, but some (e.g., supported Ni catalysts) require temperatures above 1000°C. Others have high conversion efficiency at temperatures in the range of 650-700°C. As these temperatures are well above PEM fuel cell operating temperatures, some of the fuel or, perhaps, the fuel cell purge gas, would need to be burned to sustain an efficient reaction.

Table 2-4 Ammonia cracking technologies

Technology	Technical readiness level (TRL)
Ammonia cracking (>700°C)	• 7-9
Ammonia cracking (>450°C)	• 2-4
Ammonia purification	• 3-6

2.2 Country Selection

The current study will focus on four countries that are considered to be of utmost importance in the emerging green ammonia market. The selection of these countries and the justification for their inclusion in the report is analysed in the following sections.

2.2.1 Chile

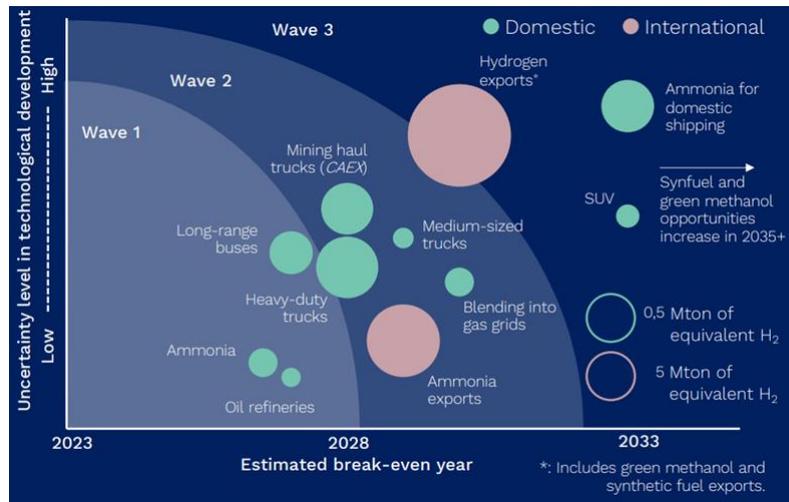
Currently, Chile is a major importer of ammonia. According to the World Bank, Chile imported about 347,000 tonnes of ammonia in 2019, at a cost of 91 million USD. The bulk of this comes from Trinidad & Tobago and the United States (Rouwenhorst, 2023). However, the country is at the forefront of developing a competitive green hydrogen industry and one of the major candidates for becoming the cheapest Green H₂ producer worldwide given its renewable resources and ability to attract investment in large-scale clean energy projects. Characteristic facts of the unparalleled RES potential in the country are the following (Ministry of Energy, Government of Chile, 2021):

- Chile's North experiences the most intense solar radiation on Earth. Monofacial solar photovoltaic plants with 1-axis tracking can achieve capacity factors of 35%.
- Solar energy generation in central Chile is already more cost-effective than traditional fossil fuel-based electricity generation. This renewable potential is strategically located near major consumption centres, gas grids as well as ports.
- The winds in the southernmost part of Chile are equally strong on land as they are offshore. Onshore wind turbines can achieve capacity factors in the range of 70%, which is comparable to offshore performance in other countries.

As such, in November 2020 the Chilean government launched the green hydrogen national strategy, which seeks to place Chile among the world's leading producers of this renewable hydrogen and its derivatives. This

opportunity will unfold in three distinct waves as indicated in Figure 2-6, with ammonia playing a pivotal role in all of those.

Figure 2-6 Projected development of green H2 applications based on McKinsey & Company



The first wave will be restricted to domestic usage of hydrogen and its derivatives. As such, grey ammonia used in mining and fertilizers will be replaced by local green ammonia production. According to McKinsey, domestic application anticipation of green ammonia will reach a total market size of 0.5 billion USD by 2050 (McKinsey and Company, 2020).

In the second wave, initiating before the end of the current decade, export activities will be put in place and local use will be expanded. The first international application, as presented in Figure 2-6, is planned to be ammonia exports worldwide.

In the third wave, expansion into new export markets is the target, leading to a substantial increase in production on a large scale. Additionally, capturing opportunities in future technologies, including for example ammonia as a shipping fuel, will be brought on the focus. By 2050, the market size of green ammonia is projected to lie around 5 billion USD (McKinsey and Company, 2020).

2.2.2 Germany

In 2019, ammonia annual production in Germany was approximately 2.9 Mt requiring almost 26.2 TWh of fossil energy for its production (Verband der Chemischen Industry, 2020). To achieve its objective of becoming climate neutral by 2045, Germany must significantly expand its renewable energy generation. However, due to limited domestic renewable energy potential, there will be a significant requirement to import energy in the form of green hydrogen produced through electrolysis, as well as green hydrogen derivatives such as ammonia. According to IRENA's 1.5°C scenario, the major export and import markets of green ammonia are

relatively concentrated. The top seven countries hold 96% and 86% of the market respectively, with their specifics quantities as presented in Figure 2-8 and Figure 2-7.¹⁶

Figure 2-8 Import countries based on IRENA's 1.5 °C scenario

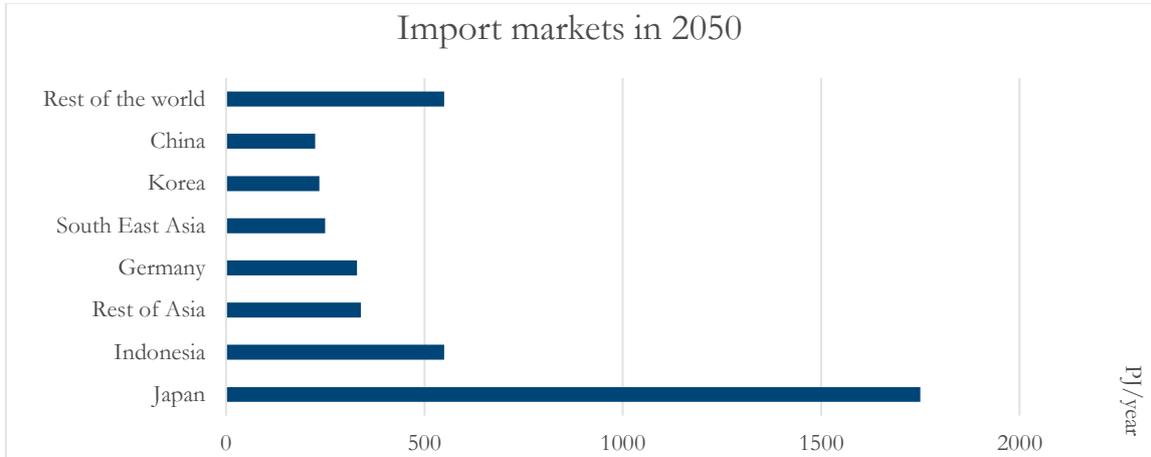
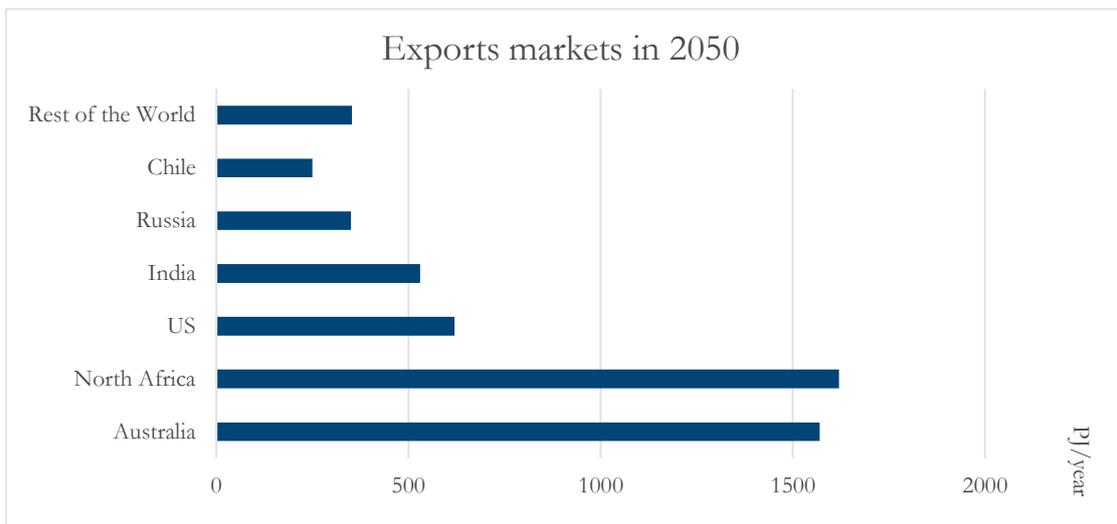


Figure 2-7 Export countries based on IRENA's 1.5 °C scenario



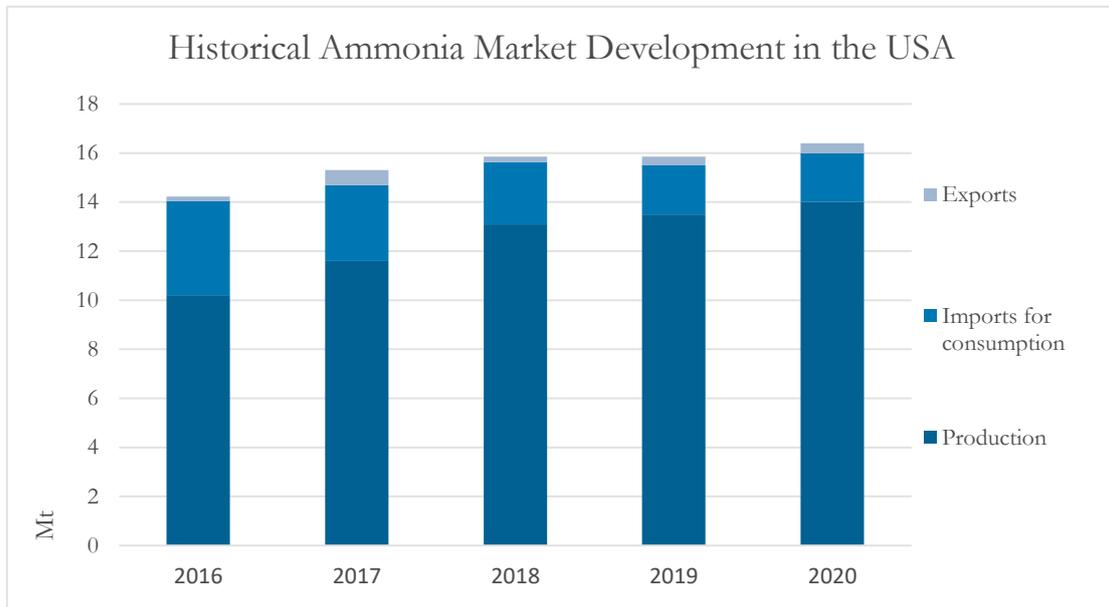
As such, confirming the broad consensus that Germany will be one of the major importers, a projection of approximately 17.74 Mt imports in 2050 is expected based on this scenario.

¹⁶ The calculation is based on the LHV of ammonia equal to 18.6 MJ/kg.

2.2.3 USA

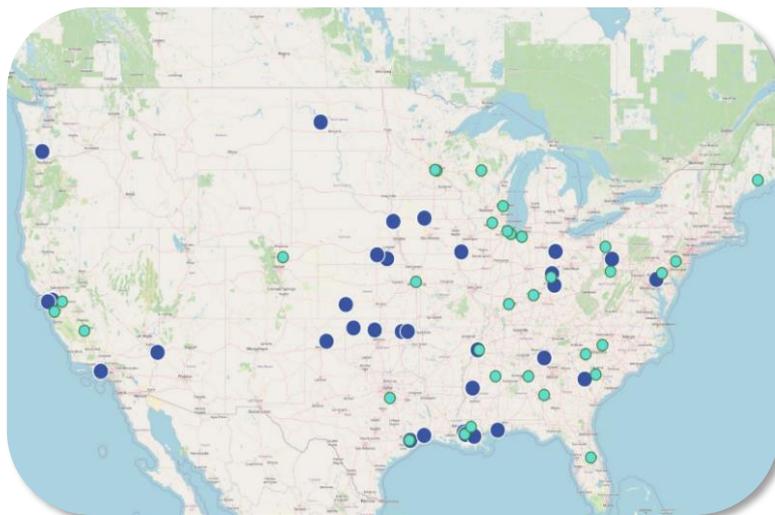
The development of the ammonia market in the USA, including imports, exports and production is presented in Figure 2-9, reflecting that the country is a major ammonia producer, reaching a domestic production of approximately 14 Mt.

Figure 2-9 Ammonia market in the USA in years 2016-2020 (USGS, 2021)



During 2020, ammonia production in the United States was carried out by 16 companies across 35 plants in 16 different states. Additionally, there were 2 plants that remained inactive throughout the year. The states of Louisiana, Oklahoma, and Texas accounted for approximately 60% of the country's ammonia production capacity due to their abundant natural gas reserves, which serves as the primary raw material for grey ammonia production (USGS, 2021). In Figure 2-10 with light blue, 36 NSF/ANSI Standard 60 Certified Suppliers are presented, whereas with dark blue, the 35 domestic production locations (EPA, 2016).

Figure 2-10 Ammonia production locations and certified suppliers in the USA (EPA, 2022)



Considering the large amounts of ammonia being produced and consumed in the country, the USA have constructed and operate important ammonia infrastructure along the whole value chain since a long time. Regarding ammonia transport, two of the longest ammonia pipelines worldwide, the Gulf Central pipeline and the MidAmerica Pipeline System (MAPCO), are in the USA. They extend in the middle of the country, covering accumulatively a distance of approximately 4,950 km. Additionally, quite large ammonia quantities are

distributed annually inland via rail and truck. By focusing on a country that has such an extensive and mature ammonia market, valuable insights and lessons can be derived that can be applied to the rest of the world as best practices.

Looking towards the future, despite having a high domestic use of fertilizer (ammonia), the United States is projected to become a major global exporter of green ammonia, according to various modelling outlooks. In fact, according to IRENA's 1.5°C scenario (refer to Figure 2-7), by 2050, the USA is projected to export over 35 Mt per year (IRENA, 2022). This suggests that while satisfying its domestic demand, which is going to be of course prioritized, the country will still have a surplus to contribute to the worldwide market, maintaining its prominent position in the global ammonia market.

2.2.4 Australia

Ammonia plays a significant role in Australia's industry, serving as a crucial input for the agriculture, mining, and manufacturing sectors. The supply of ammonia in Australia is relatively concentrated, with seven facilities operated by four companies across the country (Amandine & Cameron, 2024). Since 2010, the production of ammonia has remained stable at around 2 Mt per year (DCCEEW, 2023) (IFA). This consumption of ammonia in Australia resulted to 4.6 million tons of carbon dioxide equivalent (MtCO_{2e}) in 2021, representing about 1% of the country's annual emissions (Amandine & Cameron, 2024).

Australia is exceptionally well-positioned to harness solar energy. On top of that, with some of the world's finest wind resources, particularly along the southern and western coastlines, as well as significant hydroelectric resources in Tasmania, Victoria, and New South Wales, Australia boasts an impressive array of renewable energy. Geoscience Australia estimates that solely based on the quality of wind, solar, and hydro resources, approximately 11% of Australia's land area (equivalent to 872,000 km²) has the potential to be highly suitable for renewable hydrogen production (COAG Energy Council Hydrogen Working Group, 2019).

With such a remarkable renewable energy potential, Australia is witnessing significant advancements in the field. The country has already established a National Hydrogen Strategy in 2019, showcasing its commitment to harnessing this clean energy source. As of January 2024, according to the CSIRO's HyResource database, Australia proudly presents an extensive pipeline of hydrogen projects, amounting to a substantial investment of 127 billion AUD. Notably, among these projects, 15 have successfully passed the Final Investment Decision (FID), showcasing a great progression (Amandine & Cameron, 2024). Australia is therefore expected to have a crucial position in the global green ammonia economy, exporting worldwide, after satisfying firstly its domestic demand, similarly to the USA.

2.3 Certification of Decarbonized Fuels

In general, most countries aiming to play a role in the energy transition space, either from an export or an import perspective, do work on certification schemes to facilitate the same and equal playing field for the various stakeholders. A certification system serves as proof that specific methodologies and analytical frameworks are being applied according to a standard or set of requirements. Certifications play a vital role in establishing credibility and transparency by demonstrating to consumers that a product or service meets certain expectations. These certifications, which are issued by independent bodies, encompass both the test methods used to assess a particular product or process and the criteria that the product or process must fulfil. They can be mandatory or voluntary. Mandatory systems ensure compliance with criteria outlined in policies, regulations, or contracts, while voluntary systems are used for reporting and disclosure (IEA, 2023). An overview of some existing certification and regulatory schemes can be obtained via the following table. Additionally, the relevant links can be found in Table 7-4 of the Annex.

Table 2-5 Existing and planned regulatory frameworks and certifications for H2 and derivatives

Country	Name	Purpose	Product	Status	Criteria
Australia	Guarantee of Origin certificate scheme	Voluntary	Hydrogen, hydrogen carriers	Under development	No eligibility criteria. The only requirement is to implement an emissions accounting methodology for the hydrogen produced.
Canada	Clean Hydrogen Investment Tax Credit	Regulatory, access to tax credits	Hydrogen, ammonia	Under development	Production below certain emissions intensity levels (<0.75, 0.75-2, 2-4 g CO ₂ -eq/g H ₂). For ammonia, only one emissions intensity level is defined (<4 g CO ₂ -eq/g H ₂ -eq).
Denmark	Guarantee of Origin certificate scheme	Voluntary	Hydrogen, hydrogen-based fuels	Operational	Production from renewable electricity.
European Union	Renewable Energy Directive II	Regulatory, count against renewable energy targets	Hydrogen, hydrogen-based fuels	Operational (certification under development)	Production from renewable electricity (or grid electricity with <65 g CO ₂ -eq/kWh) meeting criteria on temporal and geographical correlation and additionality of renewable generation.
France	France Ordinance No. 2021-167	Regulatory, access to public support programmes	Hydrogen	Under development	"Low-carbon hydrogen": production with emissions intensity <3.38 g CO ₂ -eq/g H ₂ . "Renewable hydrogen": production with emissions intensity <3.38 g CO ₂ -eq/g H ₂ and renewable sources.
Japan	Basic Hydrogen Strategy	Regulatory, access to public support	Hydrogen, hydrogen-based fuels	Under development	Production with emissions intensity <3.4 g CO ₂ -eq/g H ₂
Korea	Clean Hydrogen Certification Mechanism	Regulatory, access to public support	Hydrogen	Under development	Production with emissions intensity <4 g CO ₂ -eq/g H ₂
India	Green Hydrogen Standard for India	Regulatory, access to public support	Hydrogen	Under development	Production from renewable energy with emissions intensity <2 g CO ₂ -eq/g H ₂

Country	Name	Purpose	Product	Status	Criteria
Italy	Guarantee of Origin certificate scheme	Voluntary	Electricity and renewable gases (incl. hydrogen)	Operational	Production from renewable sources.
Netherlands	Guarantee of Origin certificate scheme	Voluntary	Hydrogen	Operational	Production from renewable electricity.
Spain	Guarantee of Origin certificate scheme	Voluntary	Renewable gases (incl. hydrogen)	Operational	Production from renewable electricity.
United Kingdom	Low Carbon Hydrogen Standard: Certification Scheme	Regulatory, access to public support	Hydrogen	Operational (certification under development)	Production with emissions intensity <2.4 g CO ₂ -eq/g H ₂
United Kingdom	Renewable Transport Fuel Obligation	Regulatory, access to public support	Hydrogen (use in transport)	Under development	Production from renewable energy (excluding bioenergy) with emissions intensity <4.0 g CO ₂ -eq/g H ₂
United States	Clean Hydrogen Production Standard: Tax Credit	Regulatory, access to public support	Hydrogen	Under development	Production below certain emissions intensity levels (<0.45, 0.45-1.5, 1.5-2.5, 2.5-4 g CO ₂ -eq/g H ₂) eligible for different levels of investment tax credits support.

Figure 2-11: Existing and planned regulatory frameworks and certification systems for hydrogen and derivatives

2.4 Toxicity of Ammonia

Ammonia is a poisonous gas with an OSHA (Occupational Safety and Health Administration) exposure limit of 50 ppm. Table 2-6 presents ammonias effects on humans due to short exposures. Less is known about the effects of low-level, long-term exposures (U.S. Department of Energy, 2006).

Table 2-6 Ammonia health effects on humans

Ammonia concentration in air (ppm)	Effect on humans
5	<ul style="list-style-type: none"> Least perceptible odour.
20-50	<ul style="list-style-type: none"> Readily detectable odour.
50-100	<ul style="list-style-type: none"> No discomfort or impairment of health for prolonged exposure.
150-200	<ul style="list-style-type: none"> General discomfort and eye tearing; no lasting effect on short exposure.
400-700	<ul style="list-style-type: none"> Severe irritation of eyes, ears, nose and throat, no lasting effect on short exposure.
1,700	<ul style="list-style-type: none"> Coughing, bronchial spasms.
2,000-3,000	<ul style="list-style-type: none"> Dangerous, less than ½ hour exposure may be fatal.
5,000-10,000	<ul style="list-style-type: none"> Serious oedema, strangulation, asphyxia, rapidly fatal.
10,000 (~1%)	<ul style="list-style-type: none"> Immediately fatal.

As reflected in Table 2-6, ammonia has a pungent odour; with a detection threshold in the region of 5 ppm, whereas concentrations between 20-50 ppm in air are detectable by most people. This provides an adequate warning of its presence well below the hazardous concentration levels. However, since the toxic nature of ammonia can have substantial side effects on humans, it should be carefully handled throughout its entire value chain.

2.5 Introduction to The Safety Aspects of Ammonia

It is key to understand that the responsibility for the health & safety of personnel and for the health & safety and protection of the environment and the public, lies foremost with the facility owner / operator. Guidance in fulfilling these requirements is offered by (inter)national legislative institutions, regulators and knowledge institutes as well as the respective industry itself. However, it shall be noted that there is not a unified set of rules to be applied. Also, in most countries, there is not a comprehensive, binding set of technical rules, but rather a general framework governing the safety of process plants. Under these circumstances, codes and standards serve as one guideline to develop a safe plant. It is, however, often up to the facility owner / operator to choose which standards to apply to achieve and demonstrate safety of its plant.

The safety regulations governing the synthesis loop of anhydrous ammonia do not differ from those applicable to the storage of the ammonia. Basically, the safety aspects strongly relate to the overall volume at hand as well as the pressure and temperature under which the ammonia is contained in the various components of the plant. Obviously, when considering storage of any type, irrespective of whether moving or static storage / containment is concerned, this is where the safety risks for the larger part lie.

2.5.1 Safety, Environment and Health Documents

Regulations for the handling and storing of large volumes of chemicals like ammonia are mostly set independently by nations. However, global industry associations have come together several times to establish a more coordinated effort in managing the associated risks on an international level. One such example of a global initiative is the Strategic Approach to International Chemicals Management (SAICM), which serves as a global policy framework to promote the proper management of chemicals. The SAICM Secretariat is hosted by the United Nations Environment Program.

When it comes to handling and storing significant quantities of ammonia or similar chemicals, there are specific standards and regulations that should be followed. Some key examples include:

- SEVESO III - Directive 2012/18/EU
- OSHA PSM - Occupational Safety and Health Administration Process Safety Management (e.g. CFR 29 section 1910.38 and 1910.111) / OSHA 3132 Process Safety Management (USA)
- EPA RMP - Environmental Protection Agency Risk Management Plan (USA)
- WHS - Work Health and Safety Act (Australia)
- EPBC - Environment Protection and Biodiversity Conservation Act (Australia)
- Industrial Safety and Health Act (Act No. 57 of 1972) (Japan)
- CSCL - Chemical Substances Control Law (Japan)
- Article 184 of the Chilean Labour Code (Chile)
- Article 10 of Law 19.300, General Environmental Basis (Chile)

In the UK the COMAH - Control of Major Accidents Hazards (United Kingdom) is the basis for the safety and environmental risk management of among others, chemical facilities.

Additionally, several safety related ISO standards, which could serve as a guidance for the respective management systems at company level for the facility / plant operation are suitable for certification by accreditation firms:

- ISO 45001:2018 - Occupational Health and Safety Management Systems
- ISO 14001:2015 - Environmental Management Systems

These ISO standards are not required by the regulatory authorities and ministerial departments, to be in place and certified at the respective facility / operator / owner when permitting is concerned. However, if in place, this could ease the permitting preparation procedure significantly by having readily available the substantiation of the underlying processes and procedures relevant to the application. To some extent the content of the above may have been adopted into legislation in some countries (e.g. UK).

The SEVESO III example in the EU

The SEVESO III (Directive 2012/18/EU) is the overarching European standard adopted by all larger scale chemical and ammonia industries. So, industry-wide a well implemented and known way of working towards acceptable safety standard is in place. Seveso III (EU) covers all EU member states. Two examples of regulations applied and covered based on Seveso III in the Netherlands and Germany are the following:

- BRZO (Netherlands, for >50 ton NH₃ volumes)
- KAS18 / BImSchV and BImSchG (Germany)

Seveso III makes a classification between lower-tier establishments and upper-tier establishments. Establishment means the whole location under the control of an operator where dangerous substances are present in one or more installations, including common or related infrastructures or activities. With regard to facilities handling anhydrous ammonia, those are qualified as lower-tier establishments for quantities of more than 50 tonnes and as upper-tier establishments for quantities of more than 200 tonnes.

According to Seveso III, the operator is required to draw up a document in writing setting out the Major-Accident Prevention Policy (MAPP) and to ensure that it is properly implemented. The MAPP refers to the overall strategic and organizational approach taken by the operator of an industrial establishment to prevent major accidents involving hazardous substances. It sets out the intentions, goals, and principles guiding the prevention of such accidents and the protection of human health and the environment. The MAPP establishes the overarching framework for managing major accident risks and acts as a foundation for the Safety Management System (SMS). This SMS should consider the following elements:

- The system should be proportionate to the hazards, complexity, and activities of the organization. It should include the organizational structure, responsibilities, practices, procedures, processes, and resources for implementing the major accident prevention policy.
- The system should address the following issues:
 - Roles and responsibilities of personnel involved in managing major hazards, awareness-raising measures, and training needs.
 - Identification and evaluation of major hazards, including subcontracted activities, and assessment of their likelihood and severity.
 - Procedures for safe operation, maintenance, alarm management, and control of aging equipment and corrosion.
 - Procedures for planning modifications or designing new installations, processes, or storage facilities.
 - Procedures for identifying, preparing, testing, and reviewing emergency plans, and providing training to all personnel in the establishment.
 - Procedures for monitoring compliance with the operator's major accident prevention policy and safety management system, investigation of accidents or failures, and taking corrective action.
 - Procedures for periodic assessment and review of the major accident prevention policy, effectiveness of the safety management system, and updating by senior management based on audit and review findings.

In essence, the MAPP sets out the strategic framework and objectives, while the SMS represents the practical implementation of that policy through specific management practices, procedures, and controls. The two concepts, applicable in both lower-tier and upper-tier establishments, work together to ensure that industrial establishments effectively prevent major accidents, mitigate risks, and protect the safety of personnel and nearby communities.

In the design process, and often also helpful when performing a risk assessment, which can be required when applying for a permit, a QRA (Quantitative Risk Analysis) can be performed using software modelling tools approved by the respective legislative authorities to calculate the so-called risk contours and mitigate the effects of potential incidents, thereby preventing major accidents. It is to be noted that there is increasingly more focus on minimizing the overall QRA impact of any installation by incorporating additional equipment and selecting high-quality equipment to minimize the risk of technical failures.

Generally, the amount of ammonia or hydrogen present in a production facility is much smaller than the quantities of finished products stored for transportation or future use. Nevertheless, the failure rate is a little higher (gas is not so important if it leaks, neither ammonia nor hydrogen gas as these have a low effect on the QRA; it is the liquid which is the main contributor to the QRA).

Therefore, the design tries to keep the amount of buffering ammonia (necessary to keep the process running in steady state mode) as low as possible. One such a design measure is implementation of fast acting closing valves.

In addition to design considerations, quality control in supplies, construction, and other areas are growing in importance. Third-party specialists are often hired to conduct testing, monitor plant's mechanical and material integrity, and provide training to personnel and staff.

2.5.2 Safety, Inherently Safe Engineering & Design Documents

The following exemplary list of codes and standards are typically applied to the design, procurement and construction phases of the ammonia facilities, as well as during the operation & maintenance procedures:

- IEC codes 61508 and 61511
- ASME/ANSI CODES:
 - ANSI/CGA G-2.1 2014 Requirements for the storage and handling of Anhydrous ammonia – Sixth edition
 - ASME VIII Div. 1 and Div. 2
 - ASME B31.1-2001 (Power) Piping
 - ASME B31.12-2011 Hydrogen Piping and Pipelines
- ASTM Codes (materials)
- INTERNATIONAL MECHANICAL CODE 2012
- PED, AD 2000, DIN Standards & EN Norms
- IEC Codes for electrical appliances / instruments,
- Canadian Electrical Code (CE code)
- Atmosphères Explosibles (ATEX) directives
- National Fire Protection Association (NFPA)
- API 620
- EN 14620
- PGS-12: Ammonia storage and loading (Dutch regulation)

Safety Environment Health codes are covered in:

- API 750-Management of Process Hazard

The final listing of applicable Codes & Standards is normally considered during the EPC phase of a project and hence needs to be in place prior to start of said EPC work. Based on the above, the plant will be designed as much as possible in a way which makes it inherently safe, not only for the workers or staffers working at the facility but also for the environment (including other industrial facilities, urban activities, nature, etc.)

Most of the design codes and standards for production facilities are aiming for redundancy and fail-safe systems (looking into Safety Integrity Levels of the plant or SIL), to make sure operations are safe constantly. Containment of hazardous substances is key in this approach, minimizing in the event of a mishap or accident or a natural phenomenon, like a seismic event, the spill of the hazardous substance into the environment.

In addition to codes of design and conduct, the ammonia industry, including organizations like IFA, EFMA, and IFS, also establishes its own internal guidelines and best practices. These resources are made available to their respective members.

2.5.3 Focus on the Selected Countries

To get a clearer understanding of safety, measures related to ammonia, it is necessary to delve deeper into the countries that are of interest. This will be done in the upcoming sections.

2.5.3.1 European Union (Germany and Netherlands Examples)

In Germany, the regulatory framework for safety in the hydrogen sector is well-established and comprehensive. The responsibility for ensuring the safety of systems lies with manufacturers and operators, who must comply with general laws and ordinances that define the legal framework and allocate responsibilities. One example of such regulations is the Ordinance on Industrial Safety and Health (BetrSichV), which sets out safety requirements for the handling of work equipment, including hydrogen and its derivatives, like ammonia. The operator is obliged to carry out a risk assessment, to take the protective measures determined in accordance

with the generally recognized rules of technology and, if not available, in accordance with the state of the art and only to allow the work equipment to be used once it has been determined that the use of the work equipment is safe. The risk assessment must be carried out for the hazardous substances used or produced. This example shows two fundamental features of safety regulation in Germany:

- In many cases, safety is assessed on a case-by-case basis.
- In these individual case studies, the recognized rules of technology and the state of the art are used as the basis for assessing adequate safety.

The most important stakeholders in this system are as follows:

Legislator

Legislation in the form of mandatory laws and ordinances provides the regulatory framework that plant operators and manufacturers must adhere to ensure the safety of people, the environment and the climate. The laws and regulations are designed in such a way that they define requirements and responsibilities without prescribing specific technical measures in many cases. As a result, new technologies are at least implicitly covered by this framework, whereby the responsibility for proper implementation, for example of the BetrSichV, lies with the respective operator. The recognized rules of technology serve to ensure the proper implementation of these laws and regulations.

Standard-setting institutions

Institutions such as the German Institute for Standardization (DIN), the Federal Institute for Occupational Safety and Health (BAUA) or the German Technical and Scientific Association for Gas and Water (DVGW) develop recognized rules of technology with the involvement of experts. These rules are one way of ensuring safe operation but are not mandatory in many cases.

Experts and central monitoring bodies (ZÜS)

During the approval process for installations, inspections must be carried out to ensure compliance with legal regulations. These are primarily carried out by experts (in connection with the Federal Emission Control Act) and central monitoring bodies (as part of the Industrial Safety Ordinance). The recognized rules of technology and the state of the art play an important role here as a basis for decision-making.

The body governing this safety assurance process is referred to as the KAS which stands for Kommission für Anlagensicherheit (Plant Safety Commission). The commission handles all issues / aspects related to the so called Bundes-Immissionsschutzgesetzes (BImSchG) or Federal Emission Control Act (as mentioned above) while also the BImSchV section is part of its reach concerning the operation of a facility or plant containing hazardous substances / chemicals like ammonia in relation to occupational health, etc.

In the words of the KAS itself: The KAS is composed pluralistically. It is made up of representatives of the federal authorities involved as well as the state (provincial) authorities responsible for pollution and occupational safety, science, environmental associations, trade unions, experts and approved monitoring bodies, accident insurance providers, the industry involved and the Committee for Hazardous Substances as part of the Operational Safety Committee.

This is a typical example of how industry, public authorities and other stakeholders should basically govern occupational and environmental safety concerns, bundling all expertise and opinions such that a workable and safe operation and protected environment are guaranteed to the highest extent possible.

Another EU example (Dutch) of a legislative setup

In the Netherlands the BRZO (Besluit Risico Zware Ongevallen), in English translated to “Major Accidents (Risk) Decree”, is the Dutch arrangement of the European Seveso Directive. Industries being subject to this

decree, approximately 400 companies in the country should comply with additional requirements for their permits and operations compared to companies not subject to it to fulfil all needed safety and environmental requirements towards society. Ammonia companies with more than 50 ton of ammonia at site, are qualified as a BRZO company and hence are subject to the decree. For starters, the necessary permits for such operations include for the local (on-site) safety, but for large scale ammonia companies also external (off-site) safety is an issue and should be included in the overall permitting process.

2.5.3.2 Australia

In Australia, the specific regulation that applies to high-risk workplaces is the Work Health and Safety Regulations 2011. These regulations, supported by relevant state and territory legislation, provide detailed guidelines on managing risks associated with hazardous substances. According to the WHS, liquified anhydrous ammonia is characterized as a hazardous chemical for quantities of 200 tons and above.

In terms of design standards, Australia has some country specific codes. The AS/NZS 2022:2003, titled "Storage and Handling of Anhydrous Ammonia," covers various aspects related to the safe storage and handling of anhydrous ammonia, including among others:

- Design and Construction
- Location and Safety Measures
- Operation and Testing
- Emergency Management
- Fire Protection

Regarding ammonia-based refrigeration systems, technical guidance is available in various Australian Standards, including:

- AS/NZS 5149:2016: Refrigerating systems and heat pumps, part 1-4 (supersedes AS/NZS 1677)
- AS/NZS 3788:2006: Pressure equipment – In-service inspection
- AS/NZS 3873:2001: Pressure equipment – Operation and maintenance
- The Victorian Code of Practice Ammonia Refrigeration 2010

Furthermore, the Code of Practice: Managing risks of hazardous chemicals in the workplace is an approved code of practice under section 274 of the WHS Act. It provides practical guidance on how to manage the risks associated with hazardous chemicals in the workplace and is not a legally binding document.

Towards becoming a worldwide decarbonized fuel leader

The Australian government, together with the states and territories, has committed to developing five National Hydrogen Codes of Best Practice to facilitate the development of the hydrogen sector. These codes aim to improve safety, national consistency, and the efficiency of regulatory approvals in the hydrogen and ammonia industries and are the following:

- National Code of Best Practice Hydrogen Production
- National Code of Best Practice Ammonia Production
- National Code of Best Practice Hydrogen Refueling
- National Code of Best Practice Hydrogen Appliances
- National Code of Best Practice Ammonia Appliances.

The development of these codes represents an adaptive approach to regulatory reform. They are meant to provide clear and transparent regulatory pathways for industry players in the hydrogen and ammonia sectors. By identifying regulatory obligations associated with various lifecycle activities in each jurisdiction, the codes will help companies understand how to comply with these obligations. This shall ultimately provide confidence in the timing and cost of compliance, enabling the industry to operate more efficiently. Furthermore, the codes will assist regulators in determining acceptable standards for granting approvals. Overall, the development and

implementation of these National Hydrogen Codes of Best Practice demonstrate Australia's commitment to becoming a world leader in decarbonized fuels.

2.5.3.3 Chile

While in Chile the systems may not be as integrated and optimized as in for instance the EU or the USA, the ministries / state departments most likely having legislation in place, are:

- The Ministry of Health (Ministerio de Salud)
- The Ministry of Transport and Communications (Ministerio de Transportes y Telecomunicaciones)
- The Ministry of Energy (Ministerio de Energía)
- The Ministry of the Environment (Ministerio del Medio Ambiente)
- The Ministry of Labour and Social Security (Ministerio del Trabajo y Previsión Social)

It may be a road to further integration and focus along the value chain (involving the multiple authorities including the ones mentioned above), to intensely co-operate to come to a harmonized legislation, insofar not yet in place.

OSH in Chile is governed by a robust legal framework, with the primary legislation being Article 184 of the Labour Code and Law No. 16.744. This law establishes the framework for preventing workplace accidents and occupational diseases. It is complemented by the Chilean Labour Code, which provides additional OSH provisions. Both the Ministry of Health and the Ministry of Labor and Social Security have common competencies in the verification of compliance with legal and regulatory provisions on occupational safety. The regulations of the Ministry of Health current in force related to OSHA are the following:

- DS 594/1999: Regulations on basic sanitary and environmental conditions in workplaces
- DS 43/2015: Storage of hazardous substances.
- DS 57/2019: classification, labelling and notification of hazardous substances

With regards to the Ministry of Labor and Social Security, the regulations are:

- DS 44/2023: Preventive Management of Occupational Risks
- DS 109 / 1968: Regulations for the qualification and the evaluation of occupational incidents and diseases

Lastly, DS 13 / 2022 is the decree that approves the safety regulations for hydrogen installation and introduces amendments to gas installers regulations. With hydrogen production being the previous step prior to ammonia synthesis, the decree is of utmost importance for ammonia project developers.

When it comes to the environmental protection regulations in Chile (stemming from the right of people to live in an environment free of pollution established in the Constitution), the key instrument is the Environmental Impact Evaluation System (SEIA), administered by the Environmental Assessment Service (SEA). Any projects or activities (including modifications of existing plants) listed in Article 10 of Law 19.300 (General Environmental Basis) must be reviewed and approved by the SEIA. These include projects such as high-voltage power transmission lines and substations, power plants with a capacity exceeding 3 MW, nuclear reactors and their facilities, as well as oil, gas, mining, and similar pipeline projects. The Environmental Impact Assessment System is a preventive management tool, which allows the authority to determine, before a project is executed, that it:

- Complies with current environmental legislation.
- Takes responsibility for any potential significant impact to the environment.

The procedure for entering the Environmental Impact Assessment System is initiated at the request of the interested party and there are two alternatives for submitting a project or activity for environmental evaluation through the SEIA:

- Environmental Impact Declaration (DIA): The owner of the project or activity must present a DIA to the SEIA. This is the appropriate option if the project or activity does not generate significant adverse effects on the quantity and quality of renewable natural resources, population health, or involve other aspects mentioned in Article 11 of the Law.
- Environmental Impact Study (EIA): If the project or activity does generate or involve any of the effects, characteristics, or circumstances stated in Article 11 of the Law, the owner must submit an EIA to the SEIA. This is necessary for projects that pose risks to population health due to effluents, emissions, and waste, as well as projects that have significant adverse effects on renewable natural resources like land, water, and air quality.

Furthermore, environmental regulations and environmental sector permits (PAS) applicable to a specific project are reviewed on a case-by-case basis, considering various factors, including the nature of the project or its location, among others.

2.5.3.4 USA

In the US, the two main Government Regulatory Agencies which carry the authority concerning the regulatory framework when it comes to hazardous substances at work and within the environment are the following two:

- OSHA - Occupation Safety and Health Administration (part of the US Department of Labor)
- EPA - Environmental Protection Agency

A third and fourth institute could be identified as the DHS (US Department of Homeland Safety) and the DOT (US Department of Transport), which are involved as well concerning their specific fields.

Together these agencies monitor and control the safe production, transport, handling and storage of hazardous substances under the respective laws and regulations. They are supported by the industry, industry associations, science, research and environmental bodies of (non-) government nature.

Another key regulation in place governing the ammonia handling and storage space is for instance Standards - CFR 29, 1910.111, which falls under sub-part H for hazardous materials of in turn part 1910.

Section 1910.1200 App-D describes the mandatory use of Safety Data Sheets for toxic and /or hazardous substances. This is a generally applied document on a global scale and pretty much standardized.

Most aspects require proper reporting on a periodic basis towards the stakeholders, including those part of the public authorities. An example is the Emergency Planning and Community Right-to-Know Act (EPCRA). The reporting itself follows standard prescribed protocols, like the EPA SARA Tier II forms. In this way the state and local officials as well as the general public are properly informed of any operations involving hazardous materials in bulk.

When it concerns transport of hazardous substances, the DOT (Department of Transport) carries out the legislation / regulations and the enforcement thereof. The TCSA (Toxic Substances Control Act) its amendments and sub parts govern this type of activity.

2.6 Best Available Technologies and Industry Practises

2.6.1 Ammonia Synthesis Technologies

In Table 2-7, the Haber-Bosch (HB) synthesis alternative routes are presented (Rouwenhorst, 2019).

Table 2-7 Ammonia production technologies

HB Alternative	TRL	Electricity Demand (kWh/kg _{NH3})	Typical Conditions	Advantages	Disadvantages
High pressure	9	4.0	400-550°C 300-460 bar	<ul style="list-style-type: none"> Well-known technology. No sharp separation required. No refrigeration. 	<ul style="list-style-type: none"> Very high pressure and temperature. Operating safety. High capital investment.
Medium pressure	9	3.6	350-525°C 100-200 bar	<ul style="list-style-type: none"> Well-known technology. No sharp separation. 	<ul style="list-style-type: none"> Requires large scale. High pressure and temperature. Refrigeration required (high Opex). Operating safety.
Absorbent enhanced	4-5	0.7-3.1	370-400°C 10-30 bar	<ul style="list-style-type: none"> Relatively low pressure. Lower Capex and Opex. Safer operation. No refrigeration. Kinetics no longer rate limiting, recycle is rate limiting. 	<ul style="list-style-type: none"> Efficient separation required (low ammonia partial pressure).

The absorbent-enhanced HB alternative looks promising in terms of low energy demand. However, there are still significant challenges to be overcome. The main hurdle is the lack of proof of industrial-scale operation, which typically requires several years for construction and operation (5+years).

Furthermore, ongoing efforts are being made to explore and enhance alternative methods for ammonia production, as presented in Table 2-8. Unfortunately, most of these alternatives are currently far from being suitable for large-scale commercial projects, however, might be deployed for small scale decentralized setups in the near future.

Chemical looping approaches involve separate thermodynamically stable reaction intermediates. Three main approaches are being investigated for ammonia synthesis, hydrogen chemical looping, water chemical looping, and alkali or alkaline earth metal hydride chemical looping, as well as their combination with electrocatalysis. One advantageous aspect of chemical looping approaches is their ability to operate at mild pressures, including also atmospheric pressures. Electrochemical ammonia synthesis involves the anode oxidation of hydrogen or water, proton movement through a solid or liquid electrolyte, and electron flow through an external circuit to the cathode, where nitrogen is then reduced to form ammonia. As low-cost and renewable electricity becomes more prevalent, there has been a growing interest in electrochemical conversions. Lastly, the process of converting atmospheric nitrogen into nitrogenous compounds (e.g. ammonia) by living organisms is called biological nitrogen fixation. Biological nitrogen fixation is a naturally occurring process with various bacteria, blue-green algae and water ferns being able to fix atmospheric nitrogen.

Table 2-8 Potential future ammonia production technologies and their TRL

Area of Focus	Technology	TRL
Ammonia production	<ul style="list-style-type: none"> Decarbonized Haber-Bosch Chemical looping process Electrochemical production Biological nitrogen fixation production 	<ul style="list-style-type: none"> 5-9 1-4 1-3
R&D on decarbonized Haber-Bosch	<ul style="list-style-type: none"> Lower temperature (improving catalysts) Lower pressure 	<ul style="list-style-type: none"> 1-4 1-5

Table 2-9 provides an overview of available Original Equipment Manufacturers (OEMs) / Technology providers / licensors for ammonia synthesis, without the claim of completeness as well as including any kind of recommendation (Rouwenhorst, 2022).

Table 2-9 Available OEMs / ammonia production technology providers / OEMs

Scale	OEM's (production capacity)
Large (>1,000 t/d)	<ul style="list-style-type: none"> Casale (<6,000 t/day) Topsoe (<6,000 t/day) KBR (<9,500 t/day) Linde (<2,500 t/day), using Casale license ThyssenKrupp / Uhde (<4,500 t/day) Toyo (<2,700 t/day)
Medium (<1,000 t/d & > 1 t/d)	<ul style="list-style-type: none"> Casale (50-300 t/d; 300-800 t/d) Kapsom (4 t/d) Linde (230 t/day), using Casale's license. Proton Ventures (3, 10, 60 t/day), using Casale's license Stami carbon (100-500 t/day) ThyssenKrupp (50, 300 t/day) Tsubame BHB (<300 t/day)
Small scale (<1 t/d)	<ul style="list-style-type: none"> AmmPower (0.05 t/d) FuelPositive (0.3 t/d) Starfire Energy (0.1 t/d) Talus Renewables (1 t/d)

Furthermore, there is a multitude of Engineering, Procurement and Construction (EPC) contractors active for these ammonia facilities. These are, among others:

- Saipem
- Toyo
- McDermott
- Bechtel
- Technip
- Tecnicas Reunidas
- Maire (Technimont)
- Mitsubishi Heavy Industries
- Black & Veatch
- KBR
- Linde
- SNC Lavalin

It should be noted that for many of the above-mentioned EPC contractors steady and exclusive relationships do exist with the previously listed licensors. This might be more fluctuating and flexible in the future, since demand due to the energy transition will increase, likely beyond the capacity of the fixed tandems of EPC and licensor parties.

2.6.2 Green Ammonia Synthesis Interface with Upstream and Downstream Facilities

The interesting part of the technical challenge is the design and operation of an ammonia synthesis facility based on renewable power resources rather than fossil-based fuels. Apart from the scale of things, renewable power generation shows different characteristics compared to the old-fashioned fossil-based resource streams (e.g. natural gas), which were perfectly suited for the steady state operation setup of the ammonia synthesis loop. Those large-scale grey ammonia facilities are fed with hydrogen from the Steam Methane Reforming (SMR) upstream facility, which is completely integrated with the ammonia synthesis loop. However, in the case of green ammonia, the upstream portion will dramatically change, as it will be based on technology from different OEMs (i.e. renewable power generation, electrolysis, ammonia synthesis, desalination). Additionally, as excess heat is produced in the ammonia synthesis loop (exothermic reaction), integration of the synthesis loop with the upstream electrolysis might be beneficial, certainly in case of the application of SO-electrolysis technology, which requires heats as an input to its process (refer to Section 2.1.1).

Where it concerns the downstream facilities, all the green ammonia destined for fertilizer synthesis (ammonia derivatives) will be handled the same way as before, with most of this ammonia being converted at the same site into fertilizer products (both solids as well as liquids). In the contrary, ammonia serving the energy transition as a fuel or as a hydrogen carrier will have to be transported from the production locations to the consumption locations. Hence, more cryogenic large scale storage facilities will be needed.

2.6.3 Handling of Intermittent Renewable Resources in Green Ammonia Plants

Compared to the old / existing plants for grey ammonia production, the setup now needed has changed. Intermittent feed of renewable power and subsequently of hydrogen is to be handled by more or less the same synthesis loop setup, which requires different process control as well as ramp up / ramp down settings to cope with the fluctuating feed streams. This interfacing is where most technology providers now focus on aiming to handle this via sophisticated control setup to allow for the fast adaptation of the ammonia synthesis plant to the upstream changes driven by renewable power supply.

An optimisation process is key to determine how the various buffering systems need to be designed to allow for handling the intermittent hydrogen feed streams while avoiding shutting down the ammonia facility. Buffering of electrons with Battery Energy Storage System (BESS), hydrogen buffers (compressed) and/or other means of buffering of hydrogen using LOHC (Liquid Organic Hydrogen Carrier) or ammonia itself, could bring solutions to keep the facility running at a lower output avoiding extra unwanted downtime due to energy resource fluctuations. This optimisation exercise needs to take place during the initial engineering stages of any green ammonia project. The single exception is a facility which runs on a steadier state type of renewable energy being hydro power.

2.7 Exemplary Large-Scale Projects

2.7.1 The NEOM Helios Project

The NEOM Helios project in the Kingdom of Saudi Arabia (KSA) is the single biggest and yet under construction green hydrogen plant in the world, based on a consortium of three parties being NEOM, ACWA Power and Air Products bearing the name NEOM Green Hydrogen Company (NGHC). Approximately \$6.1 billion out of a total investment worth over \$8.4 billion is being offered as loan capital by a consortium consisting of 23 international and regional banks as well as Saudi sovereign funds. Among these contributors, KfW IPEX-Bank is providing \$325 million, which will primarily be utilized to finance the electrolyzers provided by ThyssenKrupp Nucera, a German company.

The project aims to produce up to 600 tonnes per day of carbon-free hydrogen by the end of 2026, in the form of green-ammonia as a cost-effective solution for the transportation and industrial sectors globally. A 30 year off-take agreement is drawn up with Air Products, covering 100% of the produced ammonia. In addition, Air products is the primary EPC contractor and the overall system's integrator (Neom, 2023).

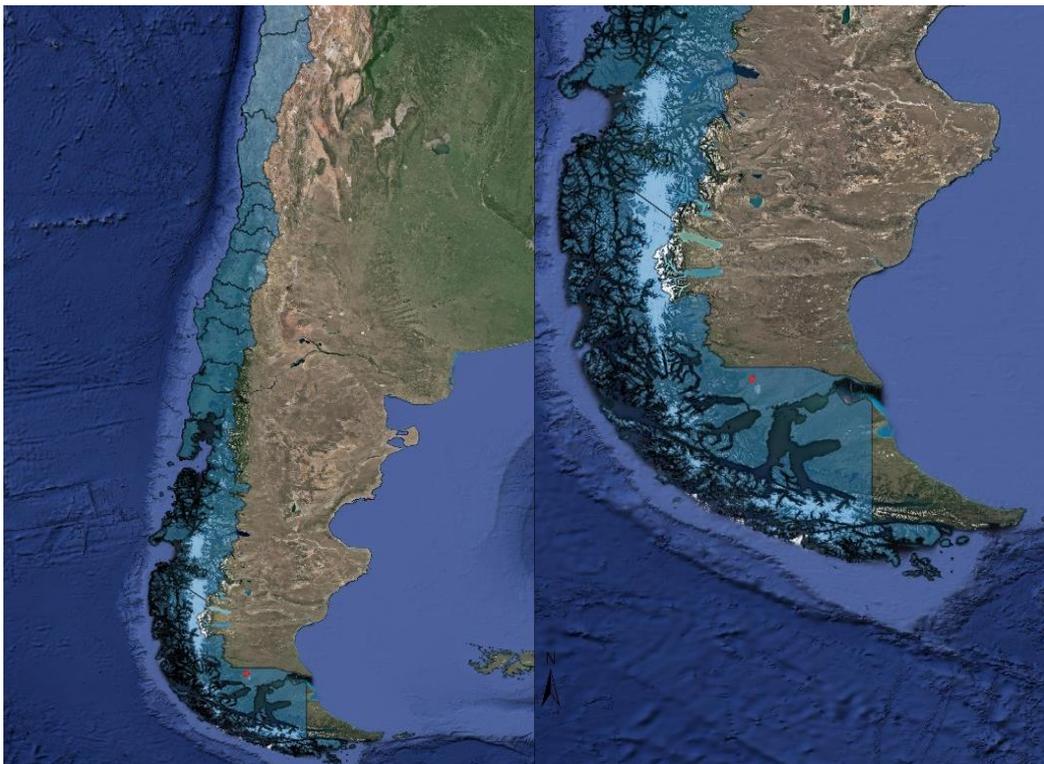
Larsen & Toubro will oversee the EPC of the upstream renewable energy generation, being based on 2.2 - 3.0 GW PV plant, a 400 MWh BESS, a 1.65 GW wind farm as well as the necessary grid infrastructure (Larsen & Tourbo, 2023). The wind farm will be based on wind turbines from Envision Energy. The industrial downstream plant is currently being built at Oxagon, in Saudi Arabia's region of NEOM. Specifically, the electrolysis is subcontracted to ThyssenKrupp Nucera implementing their 20 MW alkaline electrolyzer modular concept by means of multiplication / duplication (110 units) to reach the ultimate scale needed. Initially, early on in the development, a single 20 MW module setup will be applied as a pilot test bench. The ammonia synthesis is applying Topsoe technology based on nitrogen being provided by ASU technology from Air Products. At the point of destination, Air Products will deploy ammonia cracking technology to convert the ammonia back to hydrogen (Neom, 2023).

In general, only the above limited information is available in the public domain for the project. No more details are available regarding the permitting process as well as related third-party stakeholder influences and needs.

2.7.2 The Vientos Magallánicos Project

RWE is currently developing its first hydrogen project in Chile, the Vientos Magallánicos. The project is, at the time of writing of this report, at the feasibility stage, targeting to secure a Commercial Operation Date (COD) until Q4 2032 and aims to produce green ammonia by leveraging the vast wind potential of the Magallanes region, in the south of Chile. The product will be exported to international markets. The port selected for the time being as a reference export port is Puerto Sara. The location of the Vientos Magallánicos project is indicated in Figure 2-12.

Figure 2-12 Location of the Vientos Magallanicos Project



To achieve the targeted ammonia production, an installation of a wind plant in Villa Tehuelches will be required, composed of two plots: Predio La Invernada and Predio Bombalo. In addition to the wind plant, the Vientos Magallánicos comprises several key components, positioned as presented in Figure 2-13.

Figure 2-13 Location of the various system's components of the Vientos Magallánicos



Specifically, due to the 110 km between the Villa Tehuelches and the reference port, Puerto Sara, the following configuration will be realised:

- The process plant (hydrogen production and ammonia synthesis) will be co-located with the wind power plant in Villa Tehuelches.
- An ammonia pipeline will transport the medium from the storage facility in the ammonia synthesis plant to the export port, Puerto Sara.
- The desalination plant, together with a wastewater treatment plant, will be in the proximity of the export port.
- A water pipeline will transport desalinated water from the desalination plant close to the process plant.
- A wastewater pipeline will transport wastewater from the process plant back to the wastewater treatment plant.
- An OHL transports electricity from the wind plant to the port to secure the power supply needs of the desalination plants, as the project is entirely off-grid.

The Vientos Magallánicos project will be referenced in the current technology report to provide insights into the specific technological selections made and into how the developers addressed challenges arose. The aim is to support the future development of similar projects in Chile by explaining the decision-making process and problem-solving strategies to the extent possible.

3 SO₂ - Ammonia Production

3.1 Ammonia Production Licensors Technology Description

The goal of the current Section is to assess international ammonia licensors and provide insights, to the extent possible, on their design and technical specifications.

3.2 Publicly Available Information from Licensors

The information presented in this section relies solely on publicly available information and brochures obtained from five reputable ammonia licensors, namely Topsoe, Casale, KBR¹⁷, Thyssenkrupp¹⁸ and Stamicarbon. It should be made clear that the performance figures presented here are based on **public general data** shared by the licensors. A thorough evaluation of the licensors can only be executed based on firm quotations for a specific project with specific conditions and restrictions. Such legally binding quotations with performance guarantees can be obtained in the context of an under-development project via a tender.

3.2.1 Topsoe

One of the bigger licensors in ammonia technology is Topsoe. Originally supplying catalysts for other suppliers, Topsoe started to develop their own technology for ammonia synthesis in the mid-70s. Nowadays, the company supplies many different catalysts in the world, amongst other catalysts for ammonia synthesis.

Topsoe allows for a modularized (pre-fabricated) concept for green ammonia synthesis loops up to 600 Metric Tonnes per Day (MTPD) capacity, the so called ModuLite. To meet the most common production needs, ModuLite Green Ammonia plants are available in 300 and 600 MTPD versions. Beyond the capacity of 600 MTPD, the plant will be tailored made at the projected ammonia production plant site itself.

Dynamic flexibility in general is an important property in green ammonia plants to increase uptime and reduce the need for storage. Topsoe's green ammonia loop has the capability to adjust its load by 3% per minute and maintain a minimum stable load of 10% of its nameplate capacity, as presented in Table 3-1.

Table 3-1 Typical performance figures of Topsoe's ammonia plant

Indicator	Properties	Value	Comment
Minimum Turndown	%	10	-
Ramp Up / Down	% / min	3	-

With regard to catalysts, Topsoe's KM1 ammonia synthesis catalyst is widely used in global ammonia converters, with over 1,200 charges supplied to date. The KM1 is developed using non-exotic materials. Typically, the KM1 is only replaced during plant revamps or when new converter internals are installed. To enhance performance, it is common practice to install KM1 in the top converter bed, while KM111 is utilized in the lower beds where ammonia concentrations are higher.

Lastly, Topsoe offers to incorporate SOEC electrolyzers into its ammonia synthesis loop to optimize the overall process and provide a fully integrated solution. While SOEC can also be combined with the technology of other licensors, Topsoe is the only one of the companies discussed here that has a product for both ammonia and SOEC electrolysis. As explained in Section 2.1.1, for SO-electrolysis, heat is required for the evaporation of demineralized water prior entering the electrolyzer's stacks. Topsoe states that their solution manages to obtain 70% of the required heat for vaporization by coupling the SOEC with other downstream and waste heat-producing processes, such as ammonia synthesis.

¹⁷ Still quite often referred to as Kellogg, as Kellogg Brown & Root was formerly the name.

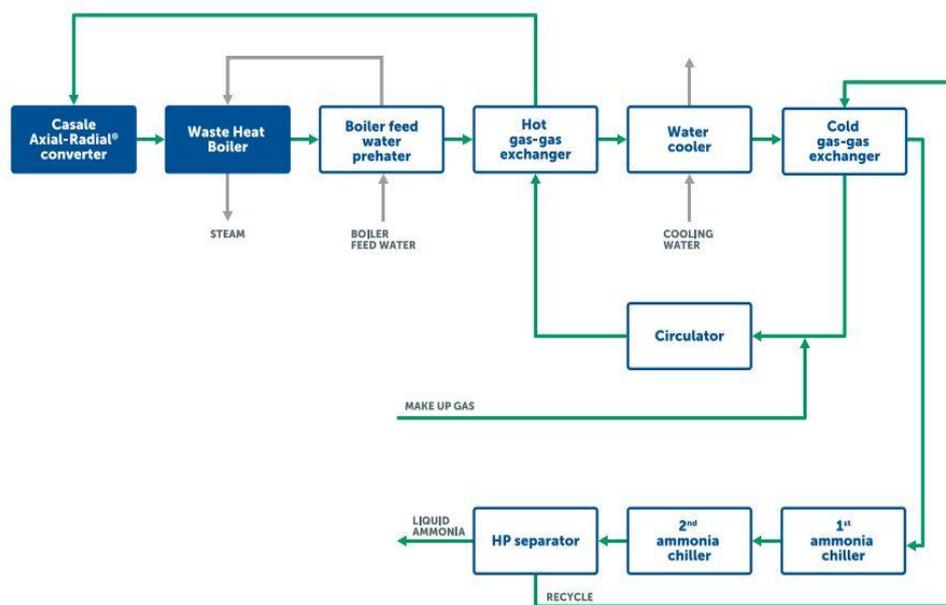
¹⁸ Still quite often referred to as Uhde, due to the founder of the company Friedrich Uhde.

3.2.2 Casale

Casale was the first licenser of ammonia technology in the early 20's of last century. In the late 80's they developed a novel synthesis loop concept and started to perform retrofitting work on existing ammonia plants, based on Thyssenkrupp and KBR technologies. From then on, they developed various other business segments in engineering and as of 2002 they were starting to license Mega ($\approx 3,000$ MTPD) ammonia technology. For ammonia loops in operation, Casale claims to have over 51% market share (including retrofitted plants).

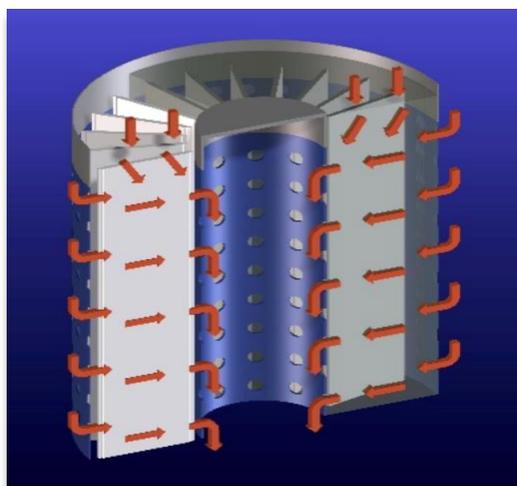
FlexAMMONIA, is the solution from Casale for large-scale green ammonia synthesis plants. Typical range of application is from 300 MTPD to 7,000 MTPD. The Block Flow Diagram (BFD) of the FlexAMMONIA's process is presented in Figure 3-1 For smaller scales, up to 300 MTPD, Casale offers the so-called SMART-IN solution, which will not be thoroughly discussed as the current focus is on large scale ammonia installations.

Figure 3-1 BFD of Casale's FlexAmmonia concept for large scale green NH₃ synthesis (Source: Casale)



Regarding the converter (reactor), Casale applies the concept of a radial - axial converter (reactor), an example of which is indicated in Figure 3-2. The Casale's specific type incorporates three adiabatic beds, with intermediate cooling by two inter-bed heat exchangers.

Figure 3-2 A radial - axial ammonia converter (TCG, 2018)



The catalyst applied is the AmoMax-Casale, a new ammonia synthesis catalyst jointly developed by Casale and Clariant for use in Casale ammonia converters. The catalyst is a customized evolution of the well-known, wustite-based catalyst, AmoMax® 10.

An interesting feature, previously applied only in smaller conventional plants, is the electric heater used by Casale for the start-up purposes of the FlexAmmonia. The role of a start-up heater is to bring and keep the system within the elevated temperature range (needed for the synthesis reaction to be properly taking place and the catalyst's lifetime control). Using an electric start-up heater instead of a traditional gas-fired type enhances the sustainability potential of the process and is the current practice used in green ammonia synthesis.

Typical performance figures of the FlexAmmonia are presented in Table 3-2. The dynamic capabilities given by Casale are in line with Topsoe's values.

Table 3-2 Typical performance figures by Casale's FlexAmmonia

Indicator	Properties	Value	Comment
Hydrogen feed gas	Nm ³ per tNH ₃	2,000	≈1% above stoichiometric
Minimum Turndown	%	10	-
Ramp Up / Down	% / min	3	-

Lastly, Casale also offers the option of retrofitting existing grey ammonia plants with hybridization (i.e. being simultaneously a green and a grey ammonia plant) through the import of green electricity. Additional components are required to realize such a retrofitting, e.g. electrolyzers, hydrogen storage, and renewable power supply (either direct or via a PPA), which of course only partly decarbonize the produced ammonia. However, it can be a mid-term solution, exploiting existing assets while increasing green ammonia's proportion incrementally.

3.2.3 KBR

M.W. Kellogg was one of the largest suppliers of technology for ammonia in the early 60s. In 1998 Kellogg merged with Brown and Root to create KBR. Brown and Root were a company having ammonia technology based on a cold box syngas cleaning technology able to reduce the hydrogen production costs, Brown plants were for years the strongly positioned in the range of up to 1,700-2,000 t/d scale, due to low costs of ammonia based on OPEX. Today, KBR claims that more than 50% of the world's ammonia is produced with KBR's technology, bringing the company at the forefront of the market. A main advantage of KBR is that it can be selected at the same time not only as technology licensor or provider, but also as the main EPC contractor, keeping everything under one roof.

KBR offer as green ammonia solution the K-Green, a full integrated solution from electrolysis of water to produce green hydrogen, separation of air to produce green nitrogen to the synthesis of green ammonia. Various capacities can be covered, specifically:

- Demonstration units (<200 MTPD)
- Small-size green ammonia plants (200-600 MTPD)
- Large scale green ammonia plants (600-6,000 MTPD)

Figures for the dynamic behavior of K-Green are not publicly available.

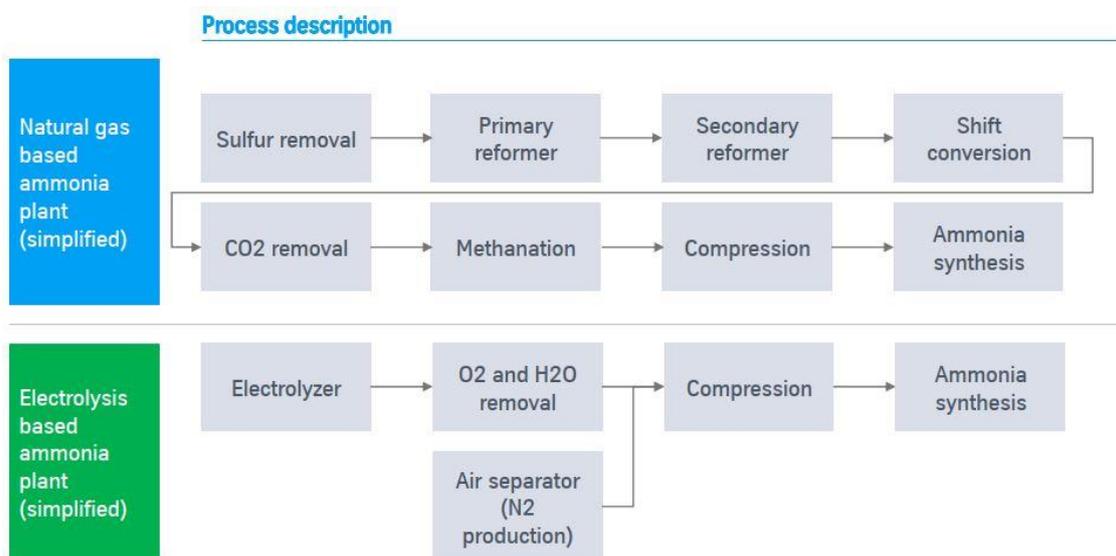
3.2.4 Thyssenkrupp

Thyssenkrupp, in short TK, is also for long time a licensor of ammonia technology. TK advertises to be the EPC contractor as well, much alike the KBR attitude, acting as a one stop shop.

The concept of Thyssen Krupp, is also based on modularization and standardization, offering plants in ranges of 300 MTPD, 600 MTPD and 1200 MTPD, basically multiplying the no. of trains implemented when scaling up facilities. In this fashion, TK can scale up production easily to approximately 5,000 MTPD.

TK indicates that for green ammonia one needs an ASU since the hydrogen production process is now different and does not use air for combustion purposes (the source of nitrogen in fossil fuel based conventional plants)¹⁹. One figure illustrating the difference between a conventional ammonia plant and an electrolysis-based ammonia plant, is found below.

Figure 3-3 BFD for a conventional and an electrolysis-based ammonia plant (Source: Thyssenkrupp)



With regard to performance figures, Thyssenkrupp discloses the following information as typical for their plants:

Table 3-3 Typical performance figures by Thyssenkrupp’s ammonia plant

Indicator	Properties	Value	Comment
Hydrogen feed gas	Nm ₃ per tNH ₃	1.995	≈1% above stoichiometric
Nitrogen feed gas	Nm ₃ / tNH ₃	665	≈1% above stoichiometric
Power	MWh / tNH ₃	10,5	For complete plant complex
Demin water	tOH ₂ O / tNH ₃	1,6	As consumption
Minimum Turndown	%	10	-
Ramp Up / Down	% / min	1,5	-
Plant availability	%	> 96	

According to TK, their ammonia plants have a minimum turndown rate as those of Topsoe and Casale, but a slower ramp up / down rate equal to 1.5% per min.

Lastly, it is noteworthy to mention, that ThyssenKrupp also manufactures and supplies AEL electrolyzers through TK Nucera, allowing them to offer integrated green ammonia plants.

¹⁹ For clarity, this is applicable in general for green ammonia, not only in Casale’s design.

3.2.5 Stamicarbon

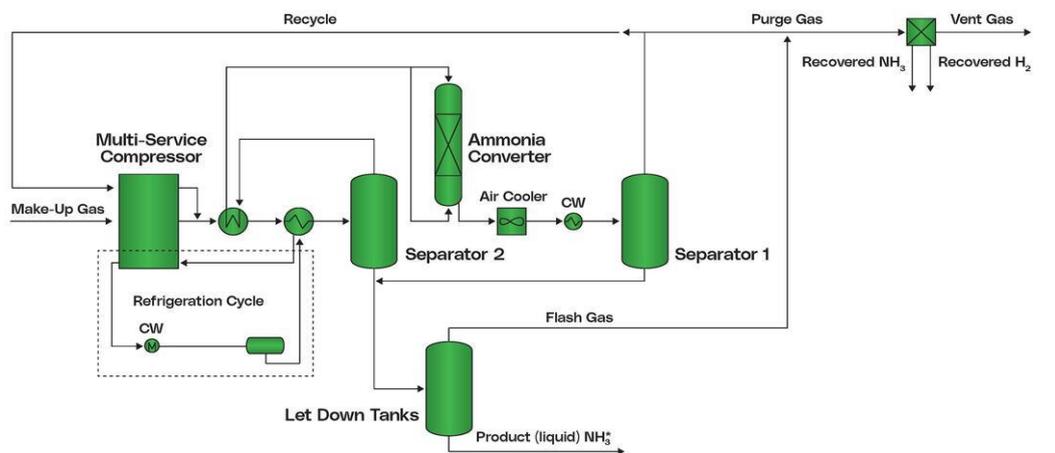
Stamicarbon is part of the Maire Group and falls within the NextChem division. Within the same group it has access to Tecnimont which is a renowned EPC contractor.

Stamicarbon has already established partnerships with the likes of Nippon Gases (ASU), Thyssen Krupp for electrolysis, Howden and Mitsubishi for compressor appliances when it comes to plants dealing with intermittency and the challenges related to this.

Stamicarbon provides green ammonia technology, suitable for up to 500 MTPD (Small-Mid size plants). The pressure is significantly higher than most larger scale commercial plants running nowadays at approximately 300 bar_g. This high pressure allows to reduce the size of all equipment, including the ammonia converter and catalyst volume. Of course, the thicker wall requirements of such a high pressure can be implemented due to the small-mid capacity of the plant. As for the reactor, an axial flow type is used, which achieves high hydrogen utilization of 99.9%. According to Stamicarbon, its lean design and reduced equipment requirements can result in a low CAPEX as well as reduced OPEX. Additionally, the company's modular plant design can provide a small footprint (50m x 50m for a 500 MTPD capacity) and potential benefits in terms of quick erection and reduced site works.

The Process Flow Diagram (PFD) of the process is presented in Figure 3-4.

Figure 3-4 Stamicarbon's Process Flow Diagram (PFD) for the green ammonia process



*warm (ambient temperature) or cold ammonia (-33 °C)

Ammonia Grades

As for the grades of anhydrous ammonia, the following three are available in the market:

- Premium Grade, “Metallurgical” – 99.995% purity
- Refrigeration Grade, “R-Grade” – 99.98% purity
- Commercial Grade, “C-Grade” or “Ag Grade” – 99.5% Purity

A “Fuel Grade” for ammonia is currently under development.

3.3 Safety Aspects of Ammonia Production

Please refer to Section 2.5 for the applicable legislation, regulations and institutions governing the HSE related aspects of large-scale ammonia production facilities. Below the current status and how the specific countries came to where they currently find themselves is described. It is noted that most aspects are addressed similarly across the globe by the major players in the ammonia industry based on a long history forming this industry. When considering the production facilities, it shows that given the safety aspects, these are generally addressed quite similarly around the world and the differences in design mostly relate to technical design setup. It strongly relates to the number of actual players in this business (primarily the technology providers) being quite limited in number.

In general, it is fair to say that currently the USA, Germany and Australia are ahead of Chile when it comes to ammonia production, transport and storage facilities at scale. Numerous facilities are in place for a prolonged period. However, it should be noted that the respective countries have built up their experience based on grey ammonia production, which is appropriate, since the ammonia technology itself is actually very similar to that of green (hydrogen-based) ammonia. No green ammonia is produced at scale yet, since most is still produced based on natural gas as the resource for the hydrogen feedstock applying SMR technology or equal. At best, one is considering low carbon ammonia based on hydrogen from natural gas through SMR technology combined with CCU or CCUS.

Chile

No green ammonia plants are operational in Chile up to the date of writing this report. Hence, the referencing to standards available within Chile and those widely applied abroad by the global industry. These standards could be applied as they are, certainly for the technical design. Alternatively, these may serve as a guidance to establish updated and more Chile focused standards when and were deemed necessary.

The commonly applied regulations and those already in place obviously do not specify which technologies are allowed, since these documents prescribe certain methodologies and certain information being required when applying for permits to build and operate. See the reference standards in Section. 2.5.1.

It is key to understand that the intrinsic safety of the production facility can be safeguarded by the international design codes and standards of which examples are mentioned in paragraph 2.5.2 which can serve as design rules for the respective facility at hand and at the discretion of the developer / operator / owner. In line with this, as previously indicated, production plant designs are selected and approved based on reputable international licensors and EPC companies that have extensive experience in building these facilities. It is always needed to demonstrate the technical integrity of the facility at hand and address safety concerns before starting operation of commercial plants.

Therefore, it is strongly recommended to use these typical international Codes and Standards for plant (equipment) design and selection once the technology to be applied is chosen.

Considering the relatively lower inventory volumes present within the production facility when comparing to for instance large scale storage tank facilities, even though some sections within the facility operate at elevated or high pressure, the focus concerning the HSE aspects will initially be on the OSHA. Subsequently, one considers the environmental risk mitigation plans for which the same regulations and standards apply as mentioned in Section 2.4.

Germany

Being the country where about a century ago the synthesis of ammonia was invented and subsequently developed towards industrial scale Germany has a longstanding reputation when it comes to health and safety considerations for both the on-site personnel as well as the broader public in the urbanized areas around the production facilities. In the early days the facilities were built at the edge of town however due growth of the townships eventually the production plants found themselves very close to or even in the middle of urbanized / populated areas.

The specific regulations / legislation in place is a result of decades of plant operation close to urbanized areas. All lessons learned from the past are embedded in those regulations and industry codes and standards. Please refer to section 2.4 for reference when it comes to a summary of the applicable regulations and design codes and standards. In general, in densely populated areas like those in Germany, it is important for the general public to have confidence that new plant constructions are intrinsically safe and that the potential effects of failures are understood.

Australia

In Australia, large ammonia production sites are in operation since a long period of time. In most cases, if not all, UK / USA based design codes and standards are being used for design as well as for benchmarking. Similarly, the permit application follows a procedure like the one in the UK. This runs through the institutions and regulations mentioned in Section 2.4.

In terms of electrical systems and equipment, the fire brigade in both the USA and Australia are typically responsible for enforcing and applying the correct codes & standards to ensure safety compliance. This means that subject public services (first responders) are often early on engaged when it comes to new developments concerning large scale chemical facilities, including for ammonia synthesis facilities.

USA

Alike Germany, the USA has a longstanding reputation for its design codes and standards, closely linked to its regulatory framework when designing installations, including equipment, valves, piping, and instruments, used in ammonia or hydrogen production facilities. Most of the codes and standards as mentioned in Section 2.4, are USA based.

Alike the setup in Australia, local fire brigades and/or auditing companies are responsible for enforcing these codes & standards.

3.4 Production Licenses for Ammonia Production

There are various options available when it comes to production licenses for ammonia. Two common methods are described below:

- **Variable License Fee** This method involves paying royalties to the technology licensor based on the amount of ammonia produced. Typically, this approach is more suitable for larger scale facilities where the volume of production makes the payment of royalties worthwhile for the licensor. A formula is used to calculate the royalty amount to be paid per ton of ammonia produced, depending on the licensor.
- **Fixed License Fee** In this method, a one-time or fixed license fee is due after the process design package is completed by the licensor. Once the process design package is available, a mechanical contractor can proceed with building the facility. The licensor requires a one-time payment in advance to secure their future income from the license. The client has the option to produce potentially more than the agreed design volume, usually between 100 and 115% capacity, based on small improvements. If there is a need to expand the plant in the future, the existing licensor or a competitor may be approached for a revamp or retrofit of the plant with new technology. This could involve additional royalties or license fees.

It is also possible to combine elements of both methods to create a hybrid licensing agreement. The specific terms and options for licensing can be customized based on the agreement between the licensor, the EPC contractor, and the client.

3.5 Positioning of the Various PtX Components

Looking the hydrogen value chain, the major blocks are:

- Renewable energy generation, e.g. wind and solar at a designated RE-site.
- Hydrogen production site, i.e. electrolysis.
- Ammonia production site.

From a geographic point of view, hydrogen and ammonia production can be located either close to the RE site or to the export harbour. Accordingly, three transport scenarios are possible (also refer to Figure 3-5):

- Transport of ammonia.
- Transport of hydrogen.
- HV electricity transmission with an OHTL.

Figure 3-5 Transport scenarios for domestic transport between RE site and export harbour



In case of entirely off-grid projects, in all three scenarios, an OHTL is required between the RE plant and the export harbour to secure the power supply of the components located in the proximity of the port²⁰. However, the electrical energy to be transmitted differs among the scenarios, with Scenario C requiring the highest amount and scenario A the lowest amount. Therefore, Scenario C will require an OHTL of a higher voltage in comparison to scenario A to restrict electrical losses.

Depending on the use-case at hand and the local framework conditions of the respective projects different transport scenarios will be more or less advantageous from a technical, economic, environmental or strategic point of view. Several aspects must be accounted for when a decision on a preferred mode of transport shall be made. Table 3-4 provides an overview of those aspects based on project experience as well as published studies.

²⁰ In Scenario C, Fichtner suggests the investigation of alternative ways to secure the power supply of the desalination plant to avoid entirely the construction of an OHTL and reduce the investment costs, should that be possible.

Table 3-4 Overview of different energy transport options

Transport Scenario	Ammonia via pipelines	Hydrogen via pipelines	Power via overhead transmission lines
Configuration	<ul style="list-style-type: none"> • Head booster station at the inlet. • Intermediate booster stations, if required. • Transport in liquid state 	<ul style="list-style-type: none"> • Head compressor station at the inlet. • Intermediate booster stations, if required. • Transport in gaseous state. 	<ul style="list-style-type: none"> • Substations needed at the start and at the end of the line. • Supporting towers. • Wide range of design configurations.
State of the Art	<ul style="list-style-type: none"> • Ammonia transport is a mature technology (refer to Section 4.1). 	<ul style="list-style-type: none"> • Pipeline networks on small scale, e.g. within industries. • Thousand km currently under development. 	<ul style="list-style-type: none"> • Widely applied and mature technology.
Corridor	<ul style="list-style-type: none"> • Safety strip of up to 12 m in width. • Depends on DN and number of strings. 		<ul style="list-style-type: none"> • Width of up to 100 m.
Permitting	<ul style="list-style-type: none"> • Ammonia is a toxic substance. • Might pose challenges to obtain permits. 	<ul style="list-style-type: none"> • Like natural gas pipelines. 	<ul style="list-style-type: none"> • The wide corridor might cause ROW challenges.
Environment and Safety	<ul style="list-style-type: none"> • Reduced visual impact (can be buried). • Environmental damage in case of leakage. 	<ul style="list-style-type: none"> • Reduced visual impact, as it can be also buried. • Hydrogen embrittlement can cause leaks. • Requires more regular inspection than other pipelines. The leakage point or puncture can grow fast while H₂ is highly flammable / explosion sensitive. 	<ul style="list-style-type: none"> • High visual impact on landscape. • Fire and electrical shock hazard. • Publicly accepted technology with regards to safety aspects.
Additional Aspects	<ul style="list-style-type: none"> • Liquid NH₃ requires smaller pipeline diameters than H₂ (lower CAPEX). • Lower capacity of booster sections compared to H₂ (lower OPEX). • A larger pipeline diameter could allow for smaller storage facilities. 	<ul style="list-style-type: none"> • Possibility to repurpose existing NG pipelines for H₂. • Lower CAPEX than construction of new pipelines. • Can be used as storage to compensate for fluctuating feed-in and off-take. 	<ul style="list-style-type: none"> • Double circuit systems offer great redundancy.

4 SO3 - Ammonia Transport

Ammonia, typically found in its gaseous state under ambient conditions, can be easily liquefied due to its low boiling point of approximately -33°C , at ambient pressure. This characteristic has led to the common practice of transporting and storing ammonia as a liquid, benefiting from its significantly reduced volume. As an internationally traded chemical, ammonia offers various transport options that cater to different scales and distances. In the following sections, an overview of these transport methods is developed.

4.1 Ammonia Transport Technologies Description

4.1.1 Transport via Pipeline

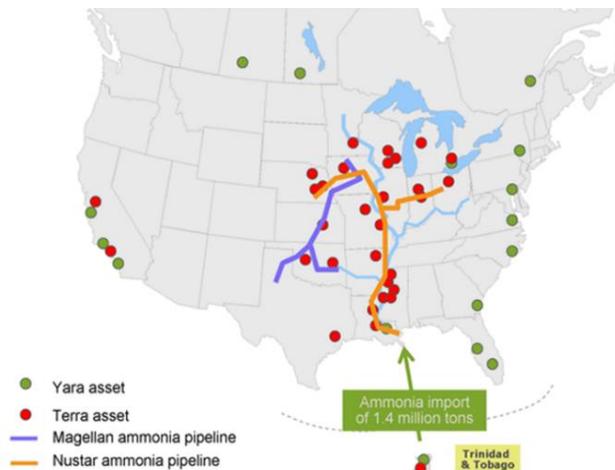
Status

In the USA, the two most noteworthy ammonia pipeline examples are the following:

- The 3,057 km Gulf Central pipeline which is the longest system and connects the major producers along the Texas and Louisiana Gulf coast with terminals in Arkansas, Iowa, Illinois, Indiana, Nebraska and Missouri (named “Nustar ammonia pipeline” due to its ownership, as referred to Figure 4-1). Its nominal capacity is equal to 1.26 Mtpa.
- The MidAmerica Pipeline System (MAPCO) which extends from Northern Texas, across Oklahoma, Kansas, Nebraska and Iowa, and ends in Minnesota, all intensive agricultural areas having a total length of 1,754 km (named “Magellan ammonia pipeline” due to its ownership, as referred to Figure 4-1). Its nominal capacity is equal to 0.9 Mtpa.

The diameters of both the pipelines are between DN 100-250, with a maximum pressure of around 100 bar_g (Elishav, Mosevitzky, Medina, & Grader, 2021).

Figure 4-1 Exemplary ammonia infrastructure in the USA (SEC)

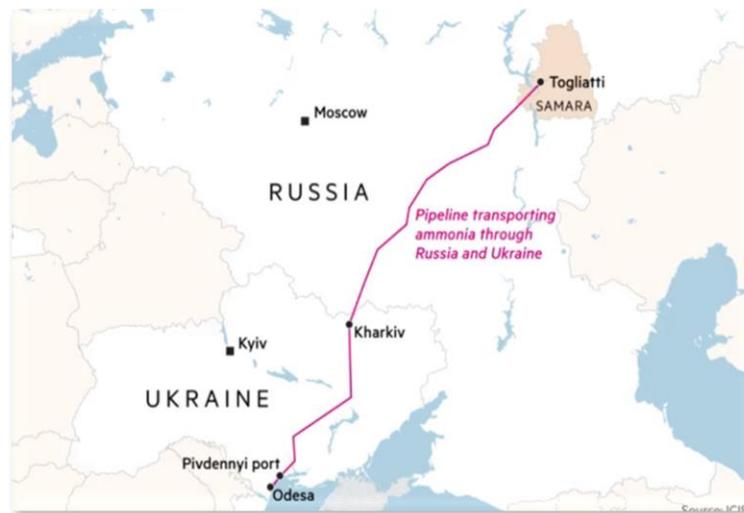


Furthermore, the Tampa Bay Pipeline, located in Hillsborough County, Florida, was commissioned in 1978 and commenced operations in the early 1980s. It serves as a vital connection between the Tampa Bay port and users in Hillsborough and Polk County. Its diameter ranges between DN 100-150, with an operating temperature of 10°C and operating pressures in the range of 20-60 bar_g (International Fertilizer Development Center, 1998).

Those three major operating ammonia pipelines in the USA sum up to a total length of approximately 4,950 km.

In Europe the Tolyatti – Odessa pipeline, being in operation since 1983, connects the large production facilities in Togliatti in Russia with the Black Sea port of Odessa in the Ukraine, covering a total length of around 2,470 km and securing an ammonia supply of approximately 2.5 Mtpa (Michelle Nichols, 2023). Ammonia is warmed up at the supplier terminal so that it can be transported at a temperature above 2°C (maximum of 30°C) and at a minimum pressure of 20 barg. Reportedly, the diameter of the line is DN 350 (Fertilizers Europe, 2009), with its route being presented in Figure 4-2.

Figure 4-2 The Tolyatti – Odessa ammonia pipeline with a length of 2,195 km, Source: ICIS



In Europe, except the Ukraine-Russia pipeline, no wide pipeline network exists, only short stretches and primarily in ports, connecting production sites with export ports or import ports with storage facilities. Such pipelines have lengths of commonly up to 10 km (reaching up to 74 km) and capacities from 0.04-5.0 Mtpa (Fertilizers Europe, 2009).

Summarizing the above, it is quite evident that ammonia pipelines are a well-established and mature technology with numerous demonstrations worldwide being able to ensure transport of large quantities of ammonia over long distances.

Operation Principle

Ammonia is transported via pipelines either as fully refrigerated liquid or as fully pressurized liquid.²¹ In both cases one or several pumping stations are deployed, depending on the distance to be covered, in order to overcome the pressure losses due to internal friction and altitude changes.

Table 4-1 Transport methods in ammonia pipelines

Method	TRL	Typical Pressure (bar _g)	Design Temperature (°C)
Non-refrigerated (fully pressurized)	9	15-30	15-25
Fully refrigerated (non-pressurized)	9	1-5	-33 to -15

²¹ Pipelines which transport gaseous ammonia are only found within the premises of ammonia production facilities and are of quite short length, as ammonia liquefaction is a relatively easy and low energy consuming process.

The major components of fully refrigerated and fully pressurized pipelines are presented in Figure 4-4 and Figure 4-3, respectively.

Figure 4-4 Major components for fully refrigerated ammonia pipeline transport

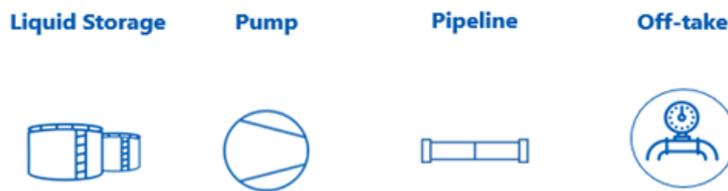
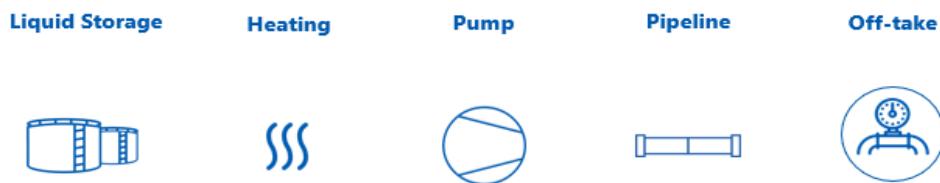


Figure 4-3 Major components for fully pressurized ammonia pipeline transport



The major difference between the two transmission methods in terms of components is that in the case of fully pressurized ammonia, ammonia has to be heated prior to long distance transport (as large-scale terminal storage is commonly fully refrigerated, refer to Section 5.2.2). In addition, refrigerated ammonia requires insulation of the pipelines and additional cooling sources to preserve the medium at the required low temperature. Thereby, it is usually applied for smaller transport distances, e.g. import and export port premises, restricted to maximum lengths of approximately 5 km (IRENA & AEM, 2022). For long distance transport via pipelines, ammonia is fully pressurized. The above statement is confirmed by the three major pipelines in the USA presented above as well as the Tolyatti-Odessa pipeline.

Challenges in Large Piping Systems

Internal Corrosion

Materials such as copper, zinc, and aluminium, which are frequently used in industrial process lines, are entirely incompatible with ammonia. For this reason, steel materials are used in ammonia transport lines. Specifically, in most cases, the material of construction is carbon steel, as it can be confirmed via the ammonia pipelines in Europe (refer to Table 4-2).

However, carbon steel is prone to Stress Corrosion Cracking (SCC). SCC is the phenomenon of cracks being formed in steel when in contact with ammonia due to the presence of oxygen. To effectively reduce SCC, it is crucial to eliminate the presence of oxygen (i.e. air). Oxygen can enter the ammonia systems through various sources such as hoses, loading and unloading pipe work, open process equipment (after a turnaround or inspection) as well as vacuum conditions. Prevention of oxygen entrance is achieved via nitrogen purging systems. As such, only after ensuring that all air has been purged should the opened ammonia equipment be put into operation. Moreover, the presence of water can inhibit the formation and growth of corrosion phenomena. Therefore, in the USA, it is prevalent to ensure that liquid ammonia contains at least 0.2% weight of water (Fertilizers Europe, 2008). Overall, SCC is a problematic phenomenon, which nonetheless can be avoided with good engineering practises and proper attention.

Lastly, it is important to note that stainless steel offers superior corrosion resistance compared to carbon steel, along with reduced maintenance costs such as sand/grit-blasting, painting, insulation removal/re-installation, and inspection (Fertilizers Europe, 2009). However, the initial investment costs for stainless steel are considerably higher, potentially even double, making the decision to choose incredibly challenging from an overall business perspective.

Table 4-2 Material selection for various European ammonia pipelines

County	Pipeline	Material
Belgium	<ul style="list-style-type: none"> • Pipeline 1 • Pipeline 2 	<ul style="list-style-type: none"> • Carbon steel TTSt35 (very fine grain) • Stainless steel 1.4541
Germany	<ul style="list-style-type: none"> • Pipeline 1 & 2, • Pipeline 3 	<ul style="list-style-type: none"> • Carbon steel (not further specified) • Carbon steel, H52-3 (similar to TSTE 355 or ASTM A 537)
Italy	<ul style="list-style-type: none"> • Pipeline 1 	<ul style="list-style-type: none"> • API 5L GrB, fully killed, Charpy V tested at -45°C
Netherlands	<ul style="list-style-type: none"> • Pipeline 1 • Pipeline 2 	<ul style="list-style-type: none"> • Carbon steel ASTM333 Gr6 and stainless steel ASTM312 TP304L • ASTM A312 TP 304L (is Symbol AISI 304L, is Number 1.4306)
Poland	<ul style="list-style-type: none"> • Pipeline 1 • Pipeline 2, 3, 4, 5 	<ul style="list-style-type: none"> • Carbon steel (no type specified) • Carbon steel type 18G2A and API 5L GrB seamless
Portugal	<ul style="list-style-type: none"> • Pipeline 1 	<ul style="list-style-type: none"> • A 333 Gr.6 / 11 st.35 / A333 Gr.1
Spain	<ul style="list-style-type: none"> • Pipeline 1 • Pipeline 2 • Pipeline 3 and 4 	<ul style="list-style-type: none"> • A 333 Gr.6 • ASTM A 333 Gr.6 • ASTM A 333 Gr.6 and St-35
U.K.	<ul style="list-style-type: none"> • Pipeline 1, 2, 3, 4, 5 • Pipeline 6 and 7 	<ul style="list-style-type: none"> • LT50 (a type of CS) and SS (type not specified) • Carbon steel (12" line)

Ice Formation

Fully refrigerated ammonia pipelines, carry the risk of ice formation on their exterior, which can have severe consequences. Firstly, the formation of ice will increase the weight of the pipeline, resulting in an increased load on pipe supports. This can potentially lead to structural issues if the supports are not designed to handle the additional weight. Secondly, there is a possibility that the ice formation can affect equipment located within the pipeline, such as isolation valves. If these components become iced in, they may become inoperable, which can potentially disrupt operations (Fertilizers Europe, 2009).

To mitigate these risks, appropriate measures are needed. One option, the most common one, is to apply vapour tight insulation to the pipeline to prevent or minimize ice formation. Alternatively, a heating system can be installed at critical locations along the pipeline. This heating system can be either electrical or steam-based, depending on the specific requirements and constraints of the system.

In terms of external corrosion, the presence of ice on the ammonia pipeline is not a significant concern. This is because the diffusion of oxygen through the ice is very slow, and the low temperature of the metal effectively reduces the corrosion rate to almost zero. Corrosion issues require specific caution when a pipeline has an intermittent operation, as in the case of a pipeline connecting a sea tanker to a storage tank. During the unloading process, the pipeline becomes cold, leading to water condensation or ice formation on its surface. When the unloading is completed and the pipeline is taken out of operation, it begins to warm up. At this point, the ice melts, and the resulting wet pipeline becomes vulnerable to corrosion (Fertilizers Europe, 2009).

Ammonia Leakage Detection

As reflected in Table 2-6, ammonia has a pungent odour; with a detection threshold in the region of 5 ppm. However, in sparsely populated areas, expecting human detection based on the intense odour of ammonia, is not feasible. Therefore, it shall be highlighted that for long pipeline systems detection of leakage can be quite challenging due to the difficulty of monitoring every section of the pipeline at a continuous base. This increases the likelihood of leaks going undetected for extended periods, potentially leading to significant environmental and safety risks.

Long transport is done fully pressurized, but large-scale storage is fully refrigerated

As explained, ammonia is transported for long distances as fully pressurized. However, large scale storage of ammonia is done at fully refrigerated facilities. In situations where the ammonia production and ammonia export locations are far apart, fully refrigerated ammonia needs to be heated before transportation and then re-refrigerated at the port premises before being stored. The heating and re-refrigeration steps require additional energy inputs, which contribute to increased energy consumption along the ammonia value chain.

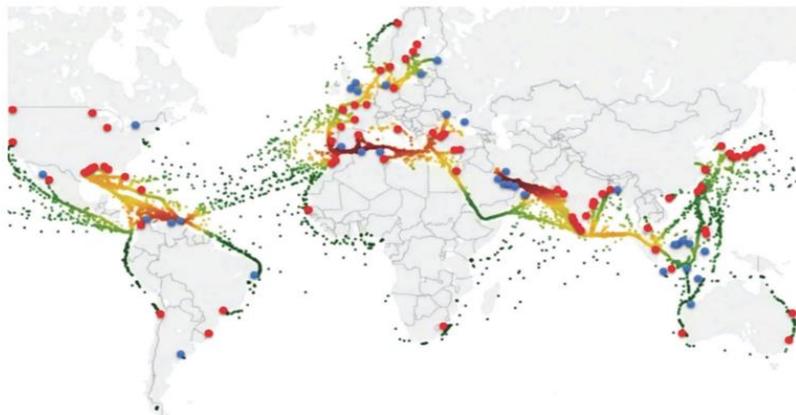
4.1.2 Transport via Shipping

Status

Overseas shipping of ammonia is a well-established business all over the world. Around 18-20 Mt of ammonia are transported annually by ship. Globally, around 170 ships are in operation that can carry ammonia, of which 40 carry ammonia on a continuous basis (Brown, 2019) (Hatfield, 2020).

Figure 4-5 presents the 2017 status of international ammonia import (red dots) and export (blue dots) facilities as well as the transport routes. The colour of the routes indicates the frequency liquid ammonia carriers are using this individual route.

Figure 4-5 Ammonia shipping infrastructure including ammonia ports (The Royal Society, 2020)



Operation Principle

Today, ammonia carriers are usually multi-purpose carriers with a tank size of up to 82,500 m³, but ships will be limited by their deadweight tonnage²². Ammonia is much denser than Liquefied Petroleum Gas (LPG) or Liquefied Natural Gas (LNG), which leads to a weight-based capacity of approximately 50,000 t cargo volume.

A list of design ships is provided in Table 4-3, in which class A to D reflects ship sizes already available in 2024. Class 2025 reflects the efforts of Namura shipbuilding to increase the cargo volume for ammonia. Ships of this size may be available in 2025. The class 2030 marks the milestone, where 100,000 t of ammonia can

²² Deadweight tonnage is the weight carrying capacity of the ship and includes the weight of cargo, fuel, lubricating oil, water, stores, crew, supplies etc. in tonnes.

be carried by ship. This may be the case in 2030. If the expected ammonia import targets are met in the future, a new carrier class will need to be deployed to avoid congestion at high volume terminals such as Rotterdam.

Table 4-3 Ammonia ships current and future classes

Class	Name	Length Overall [m]	Beam [m]	Draft [m]	Deadweight Tonnage [t]	Cargo Capacity [t]	LNH ₃ Volume [m ³]	Cargo
Qmax ²³	Future Class	345	54	12.0	170,000	160,000	235,000	
2030	Class 2030	305	50	14.0	109,000	100,000	165,000	
2025	Class 2025	230	38	12.8	89,000	80,000	132,000	
A	Large Gas Carrier	205	32	12.1	58,000	50,000	82,500	
B	Midsized Gas Carrier	180	28	10.5	27,000	25,000	38,000	
C	Handy/Small Gas Carrier	160	26	9.0	18,208	14,000	20,600	
D	Gas Supply Vessel	144	23	7.0	9,000	8,000	12,500	

Those ships are equipped with insulated tanks at temperatures between -55°C to -33°C and near atmospheric pressures. Therefore, refrigeration facilities are necessary, which, in principle, are like those of a storage facility. The ships are also equipped with pumps to sufficiently discharge the cargo at a rapid rate (Elishav, Mosevitzky, Medina, & Grader, 2021).

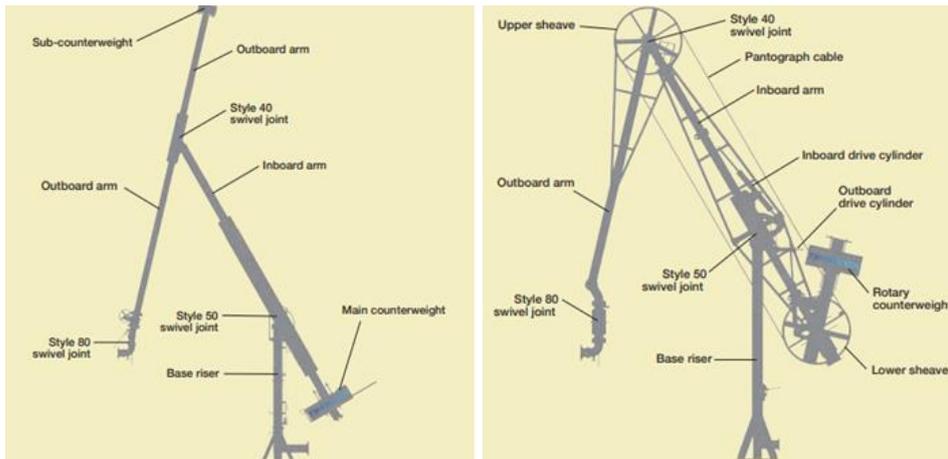
It should be noted that increasing the size of the shipping capacity is not restricted from a technical and design standpoint but from a safety one. External threats and the severity of a spillage of an even larger quantity of a toxic medium, restrict in principle a potential capacity enlargement.

To facilitate the loading and unloading of ammonia into ship tanks, cryogenic marine arms are deployed, like those used for LNG and LPG. These arms are securely mounted to the loading jetty to withstand the forces involved in the transfer process, as well as the movement of the moored ship caused by weather conditions. To provide flexibility, the loading arms are equipped with an articulated pipe system that includes rigid pipes and swivel joints. These joints are the most crucial component of the entire system, as they must withstand extremely high levels of bending and axial loads.

Traditionally those cryogenic arms are designed with cables and wheels. However, as depicted in Figure 4-6, more modern designs include an integrated pantograph, which offers better balance and no need of adjustment in the field (Kanon, 2023).

²³ Q-max draft is limited to 12 m (Port of Ras Laffan, Qatar).

Figure 4-6 Possible ship loading arms design (TB Global Technologies Ltd., 2021)



Additional components of cryogenic marine arms are the counterweights, which are strategically positioned along the arm to ensure balance and stability during the loading and unloading process. Furthermore, loading arms can be equipped with an Emergency Release Coupler (ERC), which serves as an emergency safety system, enabling a fully automatic, safe, and spillage-free disconnection of the loading arm to prevent environmental hazards. The operation of these arms is typically hydraulic, with levers located near the loading arm stand post or through push buttons on the operator's console (Kanon, 2023). While all swivel joints for different applications are applied with grease, the swivel joints for cryogenic must be constantly purged during loading, due to the fact that there is no grease in the swivel joints because it does not last in cryogenic circumstances (Kanon, 2023).

4.1.3 Transport via Rail

Status

Internationally, the importance of ammonia rail is quite considerable, being an efficient and cost-effective way of distributing large volumes of ammonia inland, offering both large capacities per journey as well as high fuel efficiencies per tonne and km. Rail is also a flexible way of transport, which for example can be used instead of barges in the case of low water levels or ice formation in the river routes. Regarding historical numbers, in western Europe more than 1.5 Mtpa of ammonia was transported by rail in 2008 (EFMA, 2008). Respectively, in the USA, there were about 52 thousand rail shipments of anhydrous ammonia, delivering approximately 4.2 Mtpa of anhydrous ammonia in 2005 (TFI, 2005).

To enable ammonia transport, Rail Tank Cars (RTCs) are deployed with an example given via Figure 4-6 (VTG).

Figure 4-7 A RTC example by VTG for ammonia transport with a payload of 55 tons (VTG)



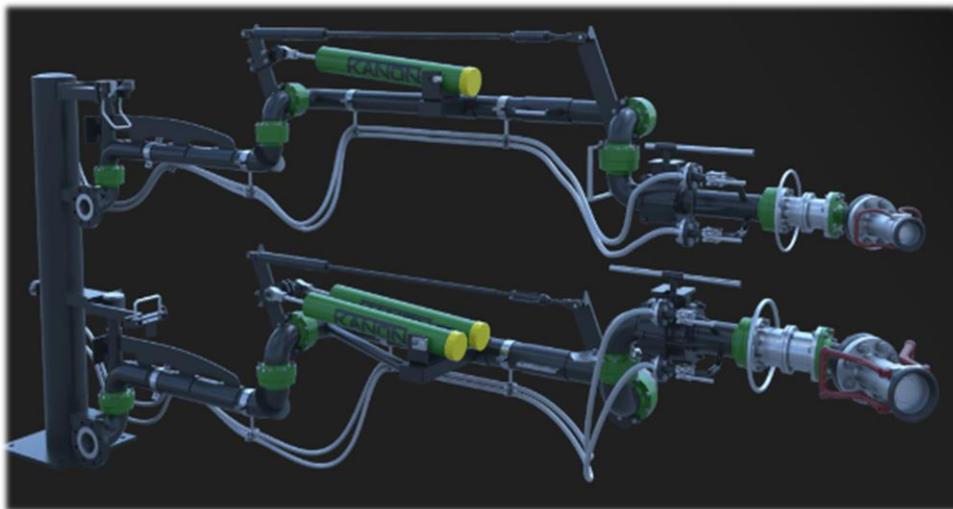
Operation Principle

RTCs have a wide range of volume capacities, typically ranging from 50 to 110 m³. In the USA, most cars have transport capacities between 65 and 72 tonnes. However, there are also smaller cars with capacities of 25 to 30 tonnes, as well as larger cars with capacities of 90 tonnes (Hignett, 1985). In RTCs, ammonia is being transported as a pressurized liquid at a pressure in the range of 15-16 bar_g (Barbers, 2008). Due to the expansion with temperature limits, the loading of ammonia is only restricted to 75-85% of the overall tank's volume (Hassan, 2009).

Typically, the design and construction of shells should adhere to the guidelines of a recognized technical code approved by the relevant authority. This code specifies the selection of materials and determines the appropriate wall thickness based on considerations such as the maximum and minimum temperatures during filling and operation (EFMA, 2008). In essence, any materials that come into contact with ammonia must not contain substances that could react dangerously with it, form hazardous compounds, degrade the material properties, or impact the quality of the ammonia. As a result, the use of copper or copper-containing materials is excluded. The shells must be constructed from metallic materials that are suitable and resistant to brittle fracture and SCC within the temperature range of -20°C to +50°C (according to RID²⁴ 6.8.2.1.8).

Regarding the filling process, loading arms for RTCs or trucks are differentiated among bottom and top loading arms depending on the positioning of the arms on the tank. The first are used for loading from the rear side or bottom (more common case), whereas the latter from the top of the tank. In the case of ammonia, a closed loop transfer is necessary, with one loading arm for the liquid transfer and one loading arm for the vapor recovery (Kanon, 2023). An example of a closed loop ammonia loading arm by Kanon is presented in Figure 4-8.

Figure 4-8 Bottom loading arm by Kanon with a closed loop (Kanon, 2024)



²⁴ International Carriage of Dangerous Goods by Rail.

4.1.4 Transport via Trucks

Status

For small scale and short distance of ammonia, trucks can be also deployed. Thereby, one of the main applications of the truck transportation is to supply retail distribution centres or small manufacturers of liquid fertilisers (Hignett, 1985).

In the USA, truck cargo tanks carried approximately 4 million tonnes of product on the nation's highways in 2005 (TFI, 2005).

Figure 4-9 A 20 ft tank ammonia truck container by VTG with a payload of 13 tonnes (VTG)



Operation Principle

In North America, ammonia is transported in MC331 cargo tanks as a pressurized liquid. Used highway trailers have a capacity of 9.5-43.5 m³ and an operating pressure of 21 bar_g, usually holding 24 tonnes of ammonia (Jeffrey Ralph Bartels , 2008).

To ensure safe operation and delivery, various safety measures are implemented. These measures include the utilization of cargo tanks designed to withstand impacts, breakaway plumbing systems that disconnect in the event of an accident, safety valves to prevent leakage from the trailer, and shutoff valves. These precautions work together to enhance safety during the transportation and handling of ammonia, varying among the design standards.

In terms of loading and unloading the ammonia cargo tanks the facilities and methodology being followed is similar as the case of the RTCs.

4.1.5 Transport via Barges

Status

Ammonia is additionally transported via barges through inland waterways (rivers and canals) or for coastal shipping. In 2005, approximately 0.9 million tonnes of anhydrous ammonia was transported by barge in the USA (TFI, 2005). Barge shipment of anhydrous ammonia is economical for countries or regions that have inland or coastal waterways and is hence, extensively used in Europe and the United States.

Figure 4-10 "Cindy Brent" upbound with anhydrous ammonia barges. (William Alden, 1999)



Operational Principle

Barges have capacities in the range of 500-3,000 tonnes, with the larger ones being fully refrigerated and the smaller ones being semi-refrigerated.

Within Europe, ammonia transfer through narrow and shallow inland waterways is facilitated by the utilization of self-propelled barges. In the United States, most barge operations are along the Mississippi River and the seaside of the Gulf of Mexico. Towed barges are a prevalent means of transportation, where multiple barges are secured together and propelled by a single tugboat. The number of barges in a tow can vary, typically ranging from 6 to 12 or even more, depending on the width of the waterway. In 2012, the total fleet of ammonia barges in the USA accounted for 31 barges (Ray Hattenbach , 2012).

4.2 Ammonia Transport Technologies Comparison

4.2.1 Definition of Comparison Criteria

Having identified the various transportation methods of ammonia, those will be compared against three key factors:

- transport distance,
- transport volume,
- continuity of supply.

By examining these factors, the aim is to gain insights into the most efficient and reliable mode of transportation for different potential scenarios. Transport distance is a crucial consideration as it directly impacts the time and cost involved in delivering ammonia from one location to another. Transport volume, on the other hand, examines the suitability of each method for handling different quantities of ammonia. Lastly, continuity refers to the uninterrupted and consistent availability of ammonia to the off-taker.

4.2.2 Qualitative Comparison of Transport Technologies

Table 4-4 Qualitative comparison of the various transport methods of ammonia

Method	Distance	Quantity per one way Trip	Continuity of Supply
Shipping	Long overseas transport.	Large quantities up to 50,000 tonnes.	No continuous supply. Prone to: <ul style="list-style-type: none"> • Adverse weather conditions (wind). • Port congestion.
Barge	Inland waterways or coastal shipping.	Large quantities up to 3,000 tonnes.	No continuous supply. Prone to: <ul style="list-style-type: none"> • Adverse weather conditions (draught, flood, ice in water ways). • Port congestion.
Pipeline	From short stretches to up to 3,000 km. ²⁵	Covers the whole range, from small to large quantities.	Continuous and uninterrupted supply.
Rail	Short or long distances, provided the rail infrastructure availability and interconnections.	Can reach large quantities in the range of 4,000 tonnes per trip and even more. ²⁶	Intermittent supply.
Truck	Maximum 150-200 km, restricted by economics.	Small quantities, up to 30 tonnes.	Intermittent supply.

As anticipated, various transportation scenarios require different methods of transport. Trucks are primarily utilized for short distances, typically up to a maximum of 200 km, due to the higher transport costs associated with smaller volumes of ammonia. Their most significant advantage is that they can reach every off-taker, even in the most remote areas.

Rail transport, on the other hand, can accommodate medium-scale transportation, allowing for significantly larger quantities compared to trucks. However, this is contingent upon the availability of existing railway lines. In both cases, the issue of empty return trips is a significant concern, as it reduces the cost efficiency.

Shipping and barges are utilized for transporting ammonia when there is a need to cross water bodies. Barges are suitable for shorter distances and smaller volumes of ammonia, including transportation along inland waterways and coastal areas. One drawback of barge transportation on rivers is the potential for interruptions caused by ice, floods, and low water levels. To account for these disruptions, terminal storage capacity needs to be expanded in proportion to the throughput, depending always on the character of each waterway. On the other hand, shipping is the only method for large-scale overseas transport of ammonia.

Lastly, pipelines are the most versatile method of transportation, capable of covering both short and long distances as well as transporting small to very large quantities. Furthermore, pipelines provide a reliable and continuous supply of resources operating 24/7. However, pipeline infrastructure entails significant initial expenses and can be time-consuming to construct, particularly when considering factors such as securing the right of way and navigating challenging terrains.

²⁵ Taking as a reference the Gulf Central Pipeline, the longest ammonia pipeline worldwide.

²⁶ Maximum ammonia cargo per trip depends highly on the capacity of the RTC deployed as well as on the in-force regulations in each country, which vary considerably in terms of maximum length per train.

4.3 Safety Aspects of Ammonia Transport

Transporting ammonia is indeed considered a high-risk activity due to its hazardous nature. However, over the past century, the number of incidents involving ammonia transport has been relatively limited. This achievement can be attributed, in part, to the lower volumes of ammonia being transported compared to other substances like crude oil and its derivatives. Nonetheless, accidents involving ammonia transport have occurred and should not be disregarded. Therefore, adherence to safety protocols is essential.

4.3.1 Transport via Pipeline

Fully refrigerated liquid streams of ammonia in a pipeline are usually found at a site or at a loading/unloading terminal, as explained in Section 4.1.1. In case of a line breakage or problem at the loading or unloading area, either by mechanical failure or by mis-operation (e.g. lack of a proper gasket), liquid ammonia is being released to the environment, creating a vast cloud of ammonia gas. The good news is that if such leakage occurs, it is usually at or close to a site where people are trained to act. Therefore, normally, trained operators or mechanics should be able to minimise the release of ammonia almost instantaneously, using automatic closing of valves, water curtains or other mitigation actions, by following well established codes of conduct. Furthermore, such facilities are commonly at a longer distance from urbanized areas and incidents reported usually do not have significant implications towards the general public. However, they do concern of course the facility's personnel affected by the (unplanned) release.

On the other hand, fully pressurized ammonia transport is the method deployed for long distances and operates at higher pressures. These pipelines are usually designed to be separate from public areas to ensure maximum safety. However, there may be instances where the general public can easily access these lines due to their long length, fact that poses challenge. Additionally, the maintenance and detection of leaks become significantly more difficult due to the extensive length of the pipelines. As a preventive measure, regular visual inspections for smaller leaks are conducted by helicopter or through ground methods, accompanied by mechanical inspections. Moreover, Emergency Shut Down (ESD) valves can be placed at a regular distance, covering sections of the pipeline of equal length or vulnerability.

Terroristic attacks shall also be prevented, but in general such long lines cannot be continuously controlled by cameras. This type of risk of attack is existent for all pipeline trajectories and cannot be completely mitigated, with a recent example being the Nord stream natural gas pipeline explosions. In conclusion, pipelines are a point of interest from a political / strategic perspective and are key infrastructure elements when it comes to intelligence agencies and threat monitoring activities by the same.

A natural phenomenon not uncommon in Chile is the occurrence of earthquakes. When designing a flow line (pipeline) for liquid ammonia not only the above described ESD valves should be implemented at reasonable distances allowing the shut in of sections of the pipeline in case of rupture, however also at regular intervals pipeline "bellows" or U-shaped sections in the pipeline could be incorporated in the design. In this way some flexibility is built into the structure along its axis. Furthermore, if mounted above ground on pipe supports, also the supports could be set up in a way allowing for some limited flexibility of the pipeline in a lateral (perpendicular) way. As an example, one could consider the long-distance crude line along the US State of Alaska which transports crude oil from the Prudhoe Bay area production location(s) in the north to the Port of Valdez in the south. One should note that the diameter of a liquid ammonia pipeline will be significantly smaller in diameter compared to crude oil line (48 inch or 1.22 meter diameter).

With regard to gaseous ammonia pipeline transport, those lines are only found within the premises of ammonia production facilities. The risks associated with the rupture of a gas line is by far less compared to an equally sized liquid ammonia pipeline (due to the essentially lower density of the medium). However, during the leakage of a gaseous ammonia pipeline, the amounts of gas released will be instantaneous creating a vapour cloud, whereas liquid ammonia requires time for the whole quantity to be evaporated.

4.3.2 *Transport via Truck*

The European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) was ratified in Geneva on September 30, 1957, with the support of the United Nations Economic Commission for Europe. This agreement came into effect on January 29, 1968.

ADR is a set of regulations that establish the necessary technical and administrative guidelines for the safe transportation of dangerous goods. All entities involved in the transportation of dangerous goods by road, including transport companies, manufacturers, distributors, and importers/exporters, are subject to compliance with the provisions outlined in the ADR.

ADR covers various aspects, including the following:

- Classification of dangerous goods
 - Ammonia is classified as a dangerous good with the number UN No. 1005.
- Establishment technical requirements for the packaging and labelling of dangerous goods, according to their class and degree of danger.
- Regulation of the documentation required for the transport of dangerous goods:
 - Documentation and authorizations are required for both the vehicle and the driver.
 - Drivers must have the special ADR license in addition to other types of permits (ID card, visa, etc.).
 - You must also have the authorization for the transport of dangerous goods ADR, plus the relevant documentation for road circulation.

4.3.3 *Transport via Rail*

For rails, non-accidental release (NAR) is a term used to describe the unintentional release of a hazardous substance from a RTC, which is not related to an accident or derailment. The issue of NARs involving anhydrous ammonia rail tank cars has been a persistent problem at loading and unloading facilities for a considerable period.

The primary causes of NARs involving anhydrous ammonia are as follows (The Fertilizer Institute):

- Deteriorated gasket on the pressure plate
- Degraded O-rings, loose connection of the pressure plate
- Absence of a valve or closure plug in the liquid line
- Leaving the valve or closure plug in the liquid line open

Aspects to consider when contracting RTCs are as follows (EFMA, 2008):

- RTCs must have explicit approval for transporting ammonia pressurized gases.
- Technical approval from the railway administration is necessary.
- Official recognition and approval from a testing and certification organization is required.
- Approval for both tank and chassis are necessary.
- Valves and fittings must be approved, and any changes made by the user should comply with the owner's rules and be part of a maintenance regime.
- Customer-specified features, such as tank shell material, pressurized tank volume, pressure rating, and type of connections, should be considered.

Upon receiving the RTCs, the filler must:

- Conduct a specific check according to a filler-specific checklist to assess the technical condition of the RTC.

- Verify all certificates of internal approval and external authority approval.
- Perform pressure testing for leaks on the tank, valves, fittings, and connections (including the discharge pipe).

In EU, the Regulation concerning the International Carriage of Dangerous Goods by Rail is RID. It is like ADR and ADN in terms of classification, packaging, labelling, and documentation requirements.

4.3.4 Transport via Vessels and Barges

Most of the ammonia shipping occurs via waterways. Vessels, barges and ISO-containers are shipped across the globe to find their destination. The safe handling of ammonia is equally important at the seller as at the buyer's site.

Handling and transferring ammonia via loading arms on jetties into ships, barges or in future as bunkering fuel of non-fossil origin and non-carbon containing, needs careful selection of subject loading / transferring equipment. In this way a suitable safety level throughout the complete supply chain from the storage tank up until the ship, barge, vessel is assured. The risk mitigation focuses mainly on the interfaces between the various intrinsically safe containment forms.

So far, in many ports across the world no "ship to ship" transfer is accepted and typically ammonia shall be first transferred (unloaded) into a shore-based storage tank, before it can be transferred (load) into another ship. Regulations allowing for subject ship to ship transfer might become effective, however up to date, this is not the "normal" practice.

Furthermore, existing ammonia producers control the flow of ammonia (especially in larger quantities) towards an existing pool of global clients, which in turn have usually implemented and hence can rely on, the proper infrastructure for ammonia transfer purposes. With new markets and transport destinations developing, this might require adoption of existing or new localized legislation for different clients willing to use ammonia for new applications. For example, bunkering ships with ammonia might require board-board loading techniques. These adopted or newly drafted regulations shall be followed-up by the established institutions and industry allowing for a scrutinizing assessment assuring that these operations are intrinsically safe. This would in turn allow for swift adoption and acceptance by local authorities / governments. Potentially, the IMO might also ask for certain rules or guidelines for this newer way of transferring / handling of ammonia.

In Europe, ADN is the EU's main regulation for the transport of dangerous goods by inland waterways. It entered into force on 29 February 2008 and aims at:

- ensuring safety of international carriage of dangerous goods by inland waterways
- contributing effectively to the protection of the environment by preventing any pollution resulting from accidents or incidents during such carriage
- facilitating transport operations and promoting international trade in dangerous goods.

Currently, ADR is adopted by 52 countries including EU and EEA countries as well as Russian Federation.

Regarding sea transport the International Maritime Dangerous Goods (IMDG) Code also applies to sea transport within EU waters. Again, IMDG classifies substances as dangerous as well as gives guidelines regarding marking, labelling and documenting. In general, the IMDG Code is of mandatory application for 166 countries parties to the International Convention for the Safety of Life at Sea (SOLAS).

4.3.5 Focus on the Selected Countries

In Australia, the Australian Dangerous Goods (ADG) Code is applicable for transport of dangerous goods by trucks as well as rails, which is published by the National Transport Commission (NTC). Regarding sea transport, the Australian Maritime Safety Authority (AMSA) oversees such activities. Australia implements the

IMO agreed international minimum requirements in Australia for all safety-related aspects of the handling and transport of cargoes and dangerous goods.

In Chile, Decree 298 of the Ministry of Transport regulates the transport of dangerous cargo on streets and roads. The definition of dangerous goods is conducted via national standards, specifically NCh382.Of89 and NCh2120/1 to 2120/9. Of 89. Lastly, NCh2190 regulates the security labels with which the dangers of the hazardous goods being transported must be identified. Within this regulation, the different kinds of labels, signs, and tags are defined, including the way of use and the places on which they must adhere.

In the USA, the Hazardous Materials Regulations (HMR) issued by the Pipeline and Hazardous Materials Safety Administration (PHMSA), which is part of the Department of Transportation (DOT). HRM govern the transportation of hazmat in all modes of transportation—air, highway, rail, and water.

4.4 Cost Comparison of Ammonia Transport Technologies

4.4.1 Inland Transport of Ammonia

Scenario Definition

In the context of mining activities, the region of Antofagasta is the most important in Chile. Such a statement is confirmed by the various active mines in the region as well as the highest energy consumption dedicated to this sector among the whole country. The latter is reflected in Table 4-5 based on data of the Ministry of Energy of Chile for 2022.

Table 4-5 The five regions in Chile with the highest energy consumption in the mining sector in 2022

Region	Tarapacá	Antofagasta	Atacama	Coquimbo	Metropolitana
Regional Consumption of Mining Sector in Tcal	4,489	31,554	7,321	3,169	3,211
Contribution to Chile's Mining Sector Energy Consumption	8%	57%	13%	6%	6%

Taking a closer look at the mining sector of Antofagasta, Table 4-6 presents the energy consumption per source, revealing the strong dependency on fossil fuels.

Table 4-6 Energy consumption per source in the mining sector of Antofagasta in 2022.

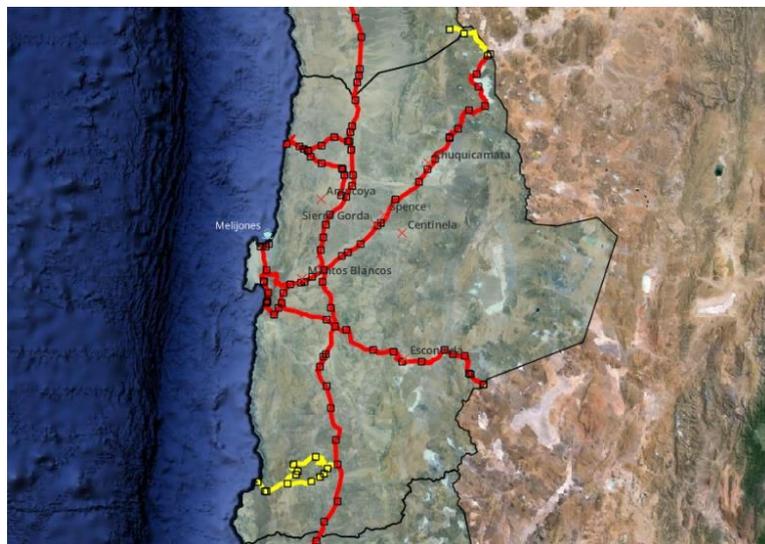
Fuel	Consumption (Tcal)	Ammonia Equivalent (kt)
Carbon Mineral	28	6.4
Diesel	15,084	3,393.0
Natural gas	1,491	335.3
LPG	95	21.3
Kerosene	107	24.1
Aviation Kerosene	196	44.0
Heavy Fuel Oil	284	63.9
Electricity	14,271	3210.1

Fuel	Consumption (Tcal)	Ammonia Equivalent (kt)
Overall Consumption	31,556	7,098.1
Fossil Fuel Consumption ²⁷	17,284	3,887,7

The fuel consumption of the fossil fuels in Antofagasta is equal to 17,284 Tcal. To cut out emissions, given the enormous solar potential of the region as well as the various green ammonia projects being currently under development, a portion of this fossil fuel consumption can be potentially substituted by green ammonia in the future.

In this context, the domestic transport of ammonia within the Antofagasta region will be assessed. Given the existing rail network in the region serving the mining sector (as presented in Figure 4-11), rail and pipeline transport methods will be compared. The transport distance is set at 200 km and the annual transport quantity at 1 Mt of ammonia²⁸.

Figure 4-11 The rail network of the mining region of Antofagasta



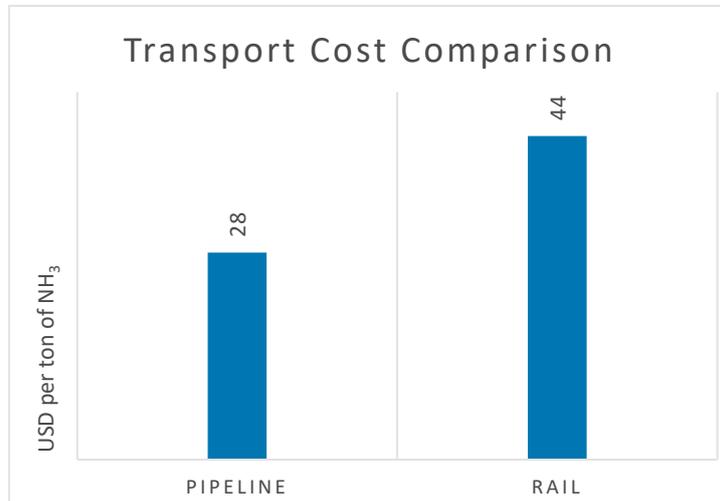
²⁷ Electricity can be directly decarbonized via electrification.

²⁸ Corresponding to approximately 25% of the current fossil fuel energy consumption and based on the LHV of ammonia being equal to 18.6 MJ/kg.

Cost Estimate Class 5

The transport cost is expressed in USD per tonne of ammonia being transported in the defined distance of 200 km. The results are summarised in Figure 4-12 and all the assumptions being made are outlined in Section 7.1.2

Figure 4-12 Cost of transporting 1 Mt of ammonia annually for 200 km via rail and pipeline



The transportation cost of rail is approximately 60% higher than the transportation cost of the pipeline. Such a result was expected due to the quite large quantity of ammonia that must be transported annually. Specifically, to secure that transport capacity, 56 RTCs must be deployed per trip and a trip must be conducted on a daily basis from the starting to the destination point. Additionally, it was considered that two locomotives are necessary to move those 56 RTCs to restrict the overall length of the train to a logical value. Therefore, the above results confirm the common consensus that for large continuous inland transport loads, even with a railway system in place, construction of a pipeline is the prevailing solution.

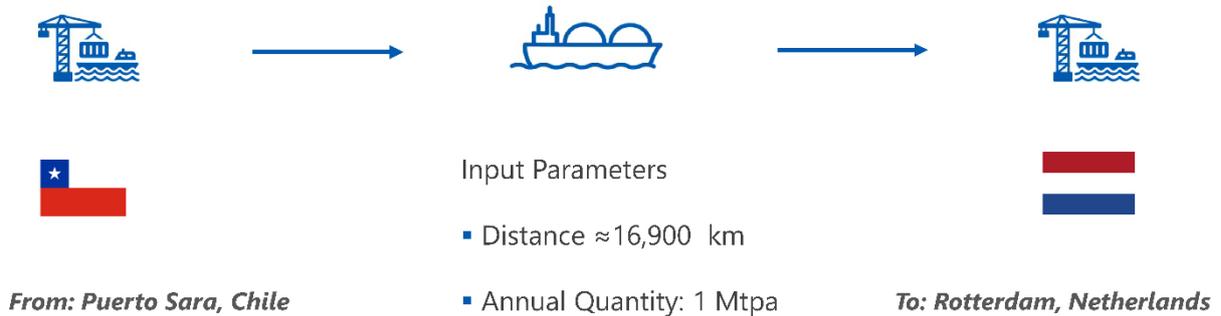
4.4.2 International Export of Ammonia

Scenario Definition

Various green ammonia projects are being currently developed in the region of Magallanes due to the vast wind potential of the region. Therefore, Fichtner will investigate the export of the product from Puerto Sara to Netherlands, a trip expected to occur often in the foreseeable future. Rotterdam, being the largest port in Europe, is selected as the destination port. Due to its value in the shipping industry and the common consensus that Europe will require large amounts of hydrogen to reach its climate objectives, the most significant share of those clean molecules is expected to be imported via the port of Rotterdam. Various studies are currently conducted to explore and untap the port's potential in the emerging hydrogen economy. One such study, led by the Port of Rotterdam authority and joined by 18 parties, investigated the feasibility of establishing a large central ammonia cracking facility in the port. This facility would produce hydrogen from imported ammonia having a capacity of generating 1 Mt of hydrogen per year. This would require a daily consumption of approximately 20,000 tonnes of ammonia (Fluor, 2023).

Figure 4-13 presents the main assumptions of the international export of ammonia scenario for which Fichtner will calculate the entailed costs.

Figure 4-13 International export scenario from south Chile to Europe



Cost Estimate Class 5

Looking at the ammonia value chain, transport-associated costs can be allocated to the handling and storage at the Port of Loading (POL), i.e. export port that would be in Chile, the shipping itself via dedicated tankers as well as the handling and storage at the Port of Discharge (POD), i.e. import port that would be in the Netherlands. Consequently, Fichtner calculated the individual contribution of each cost component to the overall transport cost of the ammonia freight, which adds up to a total of 104 USD/t. The assumptions used in the calculation are presented in the Annex 7.1.

Table 4-7 LCOAT for the international export of ammonia from Chile to Netherlands

Cost Component	Levelized Cost of Ammonia Transport (USD)
Export	22
Shipping	59
Import	23
Overall	104

The occurring transport costs are significantly lower than the expected production cost for green ammonia, but for sure not negligible. Parameters that directly influence the LCOAT include charter rates, which are the fees for hiring ships, bunker fuel prices, which affect the cost of fuelling the vessels, and canal fees, which are charges for using canals as transportation routes. Lastly, it should be made clear that if an import target of 1 Mtpa ammonia is defined, more ammonia must be produced and loaded at the export port due to boil-off gas losses during the long duration shipping.

4.5 RWE Context - Ammonia Transport

With regard to the Vientos Magallánicos, the transport of ammonia is segregated into two parts:

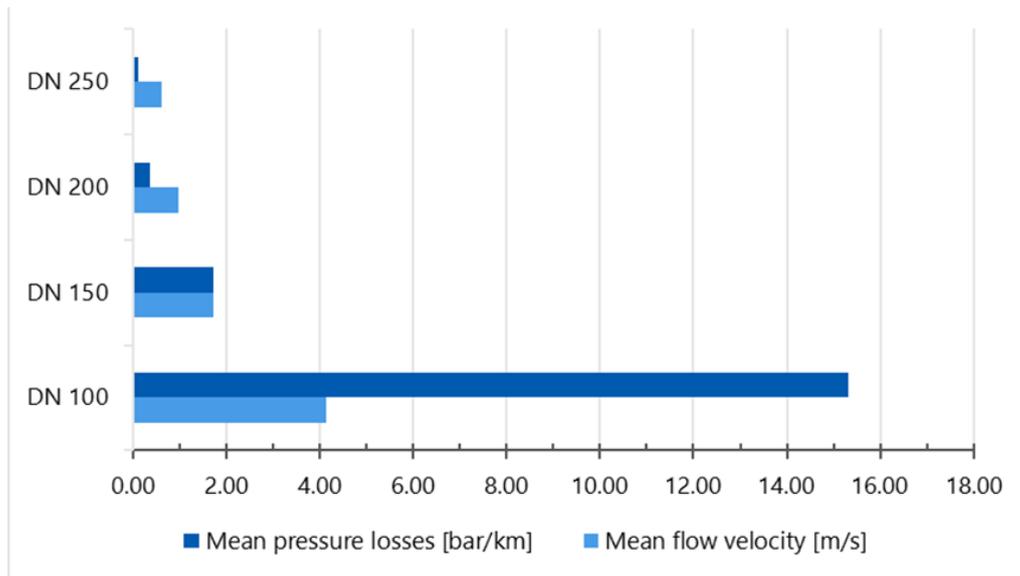
- Transport of ammonia from the ammonia synthesis plant in Villa Tehuelches to the export port, Puerto Sara, via pipeline. It should be highlighted that in the absence of a railway system in the region as well as the required continuity of the ammonia transport, a pipeline is by far the prevailing solution.
- International shipping of ammonia from Puerto Sara.

In the context of the feasibility study Fichtner conducted the preliminary conceptual design of such a pipeline. The port related works were developed by another subcontractor and as such, will not be discussed herein.

For the ammonia pipeline, its sizing was based on the design production (maximum) of the Haber Bosch process, which equals to 69 t/h (approximately 605 ktpa). A preliminary suggestion of a pipeline diameter is DN200 (DP70). Such a diameter reduces substantially the pressure losses compared to smaller diameters

and leads to lower pump duty required for the transport, as presented in Figure 4-14. This results to lower total investment costs driving the diameter selection.

Figure 4-14 Mean pressure losses and flow velocity of the ammonia pipeline for various DN



To cover the pressure losses due to internal friction and differences in altitude²⁹, a total pump duty of approximately 120 kW is required (considering the electrical motor as well). Lastly, a buried pipeline was suggested due to their enhanced safety and reduced visual impact.

5 SO₄ - Ammonia Storage and Handling

5.1 Ammonia Storage Technologies Description

Table 5-1 summarizes the three different methods for storing ammonia including their typical operating conditions (Barthers, 2008) (Ulmann, 2012).

Table 5-1 Ammonia storage methods technical characteristics

Method	Typical Pressure (bar)	Typical Temperature (°C)
Non-refrigerated (fully pressurized)	16-25	20-25
Semi-refrigerated	3-5	0
Fully refrigerated (no pressurized)	1.2	-33

5.1.1 Fully Pressurized

Pressure storage is performed at ambient temperatures and high pressures. To maintain ammonia in a liquid state at an ambient temperature of 20°C, a pressure of 8.58 bar_g is required. However, in pressure storage vessels, ammonia is kept at an even higher pressure, to ensure it remains in a liquid state even if the ambient temperature rises to high levels, as for instance in desert like environments (Barthers, 2008).

²⁹ Assuming an overall altitude difference of 300 m to be overcome.

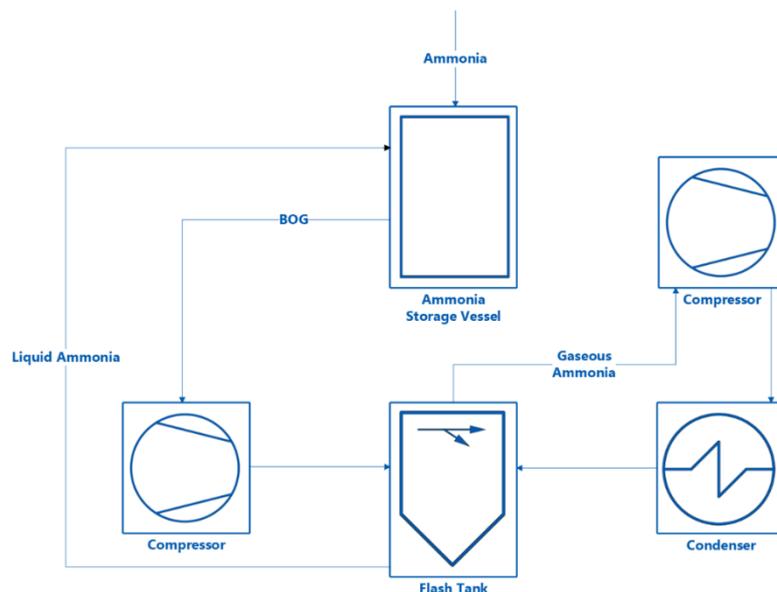
Pressure vessels come in two main types: cylindrical and spherical. Cylindrical vessels, typically horizontal in orientation, have a weight capacity of up to approximately 150 tonnes. They are designed to withstand pressures of maximum 25 bar_g. On the other hand, spherical vessels are supported by tangentially arranged columns or placed in shallow depressions. These vessels can handle weights ranging from 250 to 1,500 tonnes, ensuring static and safety considerations. Spherical vessels are designed for pressures of about 16 bar_g to avoid wall thicknesses above 30 mm (Ulmann, 2012).

An outer covering of insulation or a coat of reflecting paint is often applied on the vessels to prevent them from heating up due to solar radiation, especially in hot climates. Additionally, spraying the vessel with water, although an effective method against intense solar radiation, can cause staining and damage to the paint. To prevent stress corrosion cracking caused by ammonia, pressure vessels are commonly constructed using high-strength or fine-grained steels. However, to ensure safety and avoid this hazard, careful thermal stress relief must be carried out after all welding operations on the vessel are completed (Ulmann, 2012). This system effectively retains all the stored fuel without any loss, and it does not require additional energy to maintain the pressurized state of the fuel within the tank. Only, in case inerts like noble gases, are present, a purge system is required, which causes a little loss of ammonia.

5.1.2 Fully Refrigerated

Refrigerated storage is performed at low temperatures and ambient pressures. To maintain ammonia in a liquid state at the ambient pressure of 1 bar_g, a temperature of approximately -33°C is required. A 45,000 metric ton tank is considered as upper threshold for state-of-the-art tanks, which probably will be increased in the future. This storage method evaporates ammonia slowly in time due to the heat transferred from the environment. This is known as boil-off gas (BOG). Therefore, a two-stage refrigeration system, which uses the stored ammonia directly as the refrigerant in the refrigeration cycle, is necessary to preserve the ammonia at the low temperature as well as to cool it upon entry to the storage facility. An exemplary PFD is depicted in Figure 5-1.

Figure 5-1 Process Flow Diagram of a fully refrigerated ammonia tank



To avoid a pressure increase, a vapour line is routed from the top of the tank to the refrigeration system. The compressor transports and compresses the gas to a higher pressure and a higher temperature. The compressed ammonia vapor is condensed in an air-cooled condenser. Part of the liquid ammonia leaving the condenser is flashed and used as cooling medium for the economizer, which sub-cools the condensed stream which is then directed to the ammonia tank. The flashed ammonia is returned to the suction side of the compressor.

The design of fully refrigerated ammonia tanks follows standards such as API 620 R and EN 14620. To mitigate the effects of stress, carbon-manganese steel with a minimum yield strength in the range of 290-360 MPa is commonly chosen as the base material (welding materials should have an even higher yield strength). In terms of foundations, there are two main types. One type involves a tank resting on concrete plinths, which acts as a barrier to protect the ground below from freezing due to ammonia. This setup eliminates the need to heat the ground. The other type of foundation is when the tank is placed directly on the ground, requiring the foundation to be heated to prevent freezing (Fertilizers Europe, 2014).

Ammonia tanks can be of single wall (single containment) with external insulation as presented in Figure 5-2.

Figure 5-2 Single wall (single containment)

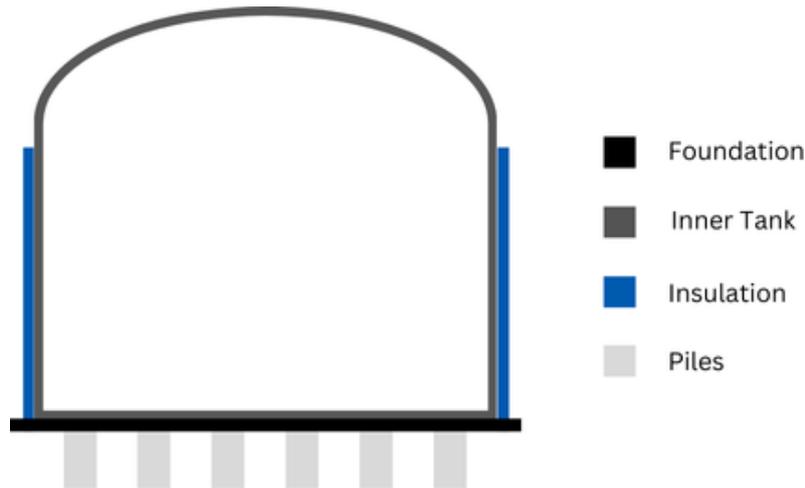
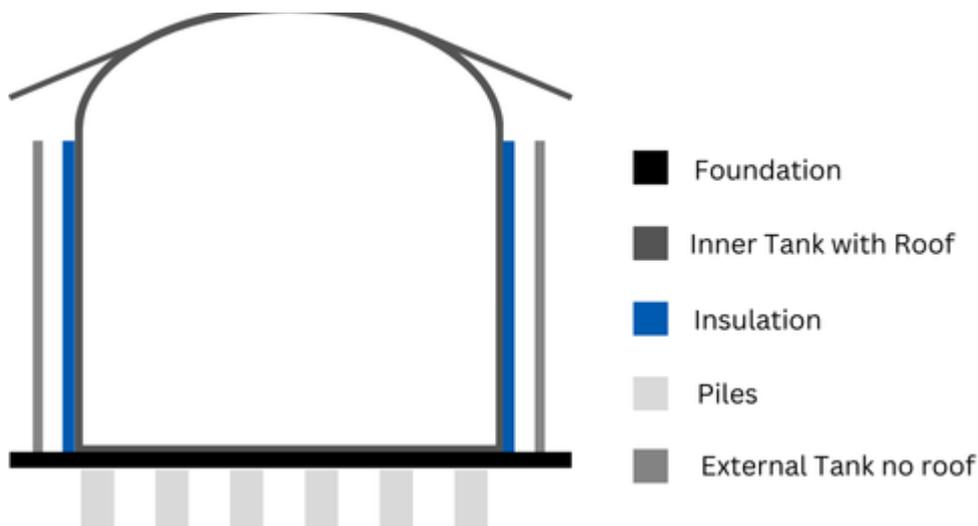


Figure 5-4: Double wall (double containment) ammonia tank

Additionally, ammonia tanks can be designed as double-wall (double containment) tanks, which allows them to capture any liquid ammonia in the event of a failure of the inner tank. Figure 5-3 illustrates an example of such tank.

Figure 5-3 Double wall tank (double containment)



However, double-wall tanks alone are not effective in preventing the release of ammonia vapours. A more advanced version, known as double wall, double integrity (DWDI) type or as full containment tanks, is required to ensure that no vapours are emitted. This can be achieved by placing perlite insulation in the annular space between the double walls or by adding insulation to the external surface of the tanks. The two variations of DWDI tanks are presented in Figure 5-5 and Figure 5-6, respectively. The significant distinction between the

two types of DWDI is that the one featuring insulation on the outer tank can continue operating for an extended period in the event of an inner tank failure. In contrast, the one with insulation in the annular space must be decommissioned if the inner tank fails since its outer part lacks insulation. However, those tanks have the advantage of lower construction costs, as insulation placed on the external surface is prone to the weather conditions.

Figure 5-5 DWDI (full containment) ammonia tank with annular space insulation

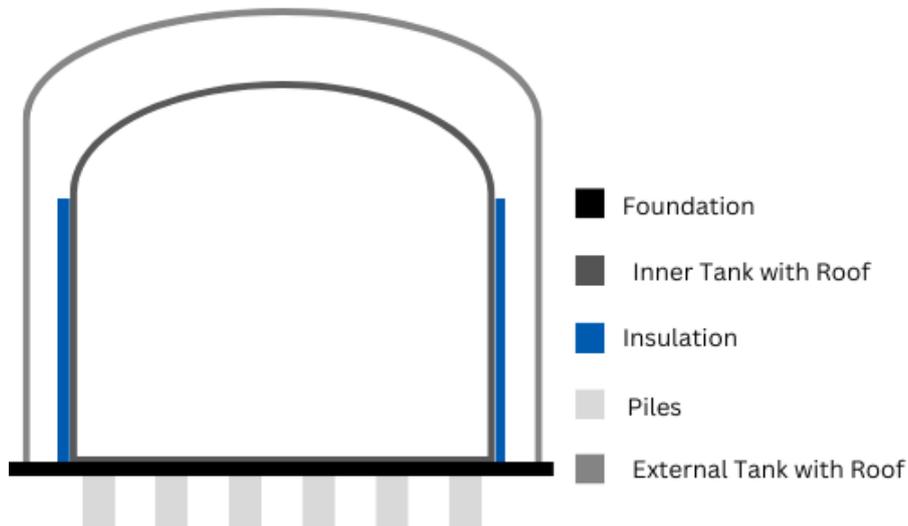
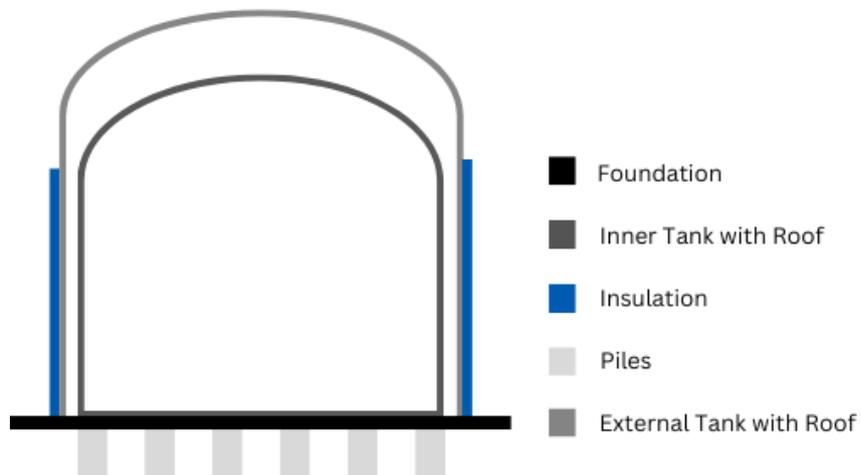


Figure 5-6 DWDI (full containment) ammonia tank with external insulation



In the past, tanks with a single wall were commonly constructed at various locations. However, it has been found that double wall tanks are safer, although they still do not fully contain ammonia vapor. As a result, current guidelines, which rely on quantitative risk assessment, recommend the use of Double Wall Double Integrity (DWDI) tanks for bulk storage. This is done to minimize risk levels as much as possible. Furthermore, it should be highlighted that a failure rate of 10^{-6} has been identified for a steel/steel tank (not protected against impact from external projectiles) versus a rate of 10^{-8} concrete/steel tank. In the emerging green ammonia industry, large-scale ammonia storage facilities will be constructed in densely populated areas, such as Rotterdam and Hamburg, making safety an imperative concern.

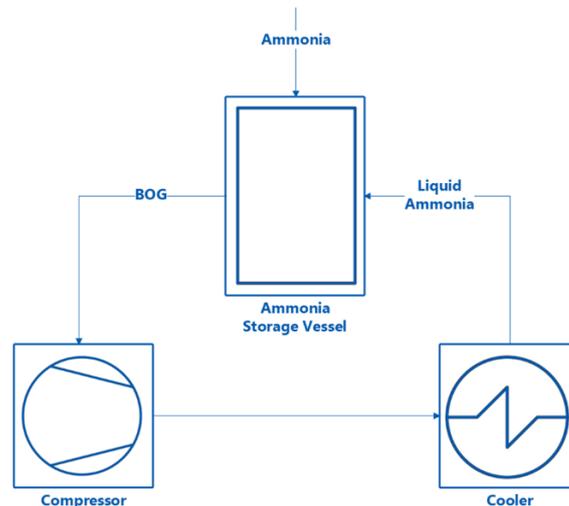
Typically, ammonia tanks are secured with bunds. A bund is a barrier made of brick, stone, or concrete that retains liquid. It is the main component of a spill containment system, and the entire system or bunded area is commonly referred to as the "bund" within the industry. The bund's capacity and strength should be designed to contain any liquid ammonia that may be accidentally released from a (full) tank. It should also be able to handle spills and leaks of above-ground ammonia and aid in cleanup operations. A typical bund consists of an

impervious wall or embankment surrounding the facility or tanks, a preferably impervious floor within the bunded area, joints in the floor or wall, and facilities designed to remove liquids from the bunded area without causing environmental pollution (Fertilizers Europe, 2014).

5.1.3 Semi-Refrigerated

In semi-refrigerated storage, ammonia is stored at pressures lower of 3-5 bar_g and at temperatures close to 0°C. Therefore, like the fully refrigerated, a refrigeration system is again needed. However, due to the lower cooling requirements, a single refrigeration stage suffices.

Figure 5-7 PFD of a semi-refrigerated ammonia tank



The BOG is compressed in a single stage to increase its pressure and temperature. Subsequently, passes through the condenser, where it releases heat and changes into a high-pressure liquid. The high-pressure liquid ammonia then flows through an expansion valve, where its pressure is reduced rapidly, in order to reach the ambient pressure conditions required and is directed back to the tank.

Semi-refrigerated ammonia tanks reach capacities up to 2,700 tonnes of ammonia serving small to medium scale applications. Typical applications are some barges as well as factories.

5.2 Ammonia Storage Technologies Comparison

5.2.1 Definition of Comparison Criteria

Having identified the various transportation methods of ammonia, those will be compared against three key factors:

- Mass of stored ammonia per mass of steel
- Storage capacity per storage unit
- Usage and type of refrigeration system (driving system's energy consumption)

Storage capacity per storage unit refers to the amount of ammonia that can be in one unit in a given storage method, considering the maximum size scale available currently in the market. Energy consumption considers the amount of energy required to maintain the stored ammonia at the desired conditions of temperature and pressure. Lastly, mass of stored ammonia per mass of steel indicates the efficiency of the storage method in terms of the amount of ammonia that can be stored per unit of steel used for the manufacture of the storage tank/vessel.

5.2.2 Qualitative Comparison of Storage Technologies

The results of the technology comparison are summarized in Table 5-2.

Table 5-2 Qualitative comparison of the ammonia storage technologies

Method	Typical pressure (bar)	Design temp. (°C)	t_{NH_3} / t_{steel} (-)	Storage capacity (kt_{NH_3})	Refrigeration System
Non-refrigerated (fully pressurized)	16-25	20-25	2.8	<1.5	None
Semi-refrigerated	3-5	0	10	0,5-2.7	Single stage
Fully-refrigerated (no pressurized)	1.2	-33	41-45	5-45	Two stages

The storage of ammonia at ambient pressure significantly reduces the steel content of the vessel. Specifically, the fully refrigerated storage requires approximately 15 times less steel in comparison with the fully pressurized. This low usage of steel, results in essentially reduced capital costs. Hence, despite the higher energy consumption associated with double-stage refrigeration, fully refrigerated storage is widely adopted for large-scale ammonia storage either in production sites or in export/import ammonia terminals.

Fully and semi-refrigerated storage systems, requiring double and single refrigeration systems respectively, are more complex due to the need for onboard refrigeration and energy consumption to preserve low temperatures. Therefore, in the case of mobile storages like trucks and rails, fully pressurized storage is preferred to avoid these complexities. Nurse tanks with a typical capacity of 3.8 m³ to 5.5 m³ are used on farms and at retailer filling facilities, mainly for agricultural applications. An additional option is using T50 ISO tank containers, which are usually constructed from stainless or carbon steel. These containers are used for ammonia transportation, with a capacity range of 11 m³ to 25 m³ (Elishav, Mosevitzky, Medina, & Grader, 2021). Furthermore, this method of pressurized ammonia is suitable in cases of balancing production variations with down-stream units processing pressurized ammonia as well as entrance to or exit from long pipeline system, in which transport is conducted at fully pressurized conditions as explained in Section Figure 5-8.

Figure 5-8 Nurse tanks to the left and T50 ISO containers to the right (Quinn, 2024)



5.3 Safety Aspects of Ammonia Storage and Handling

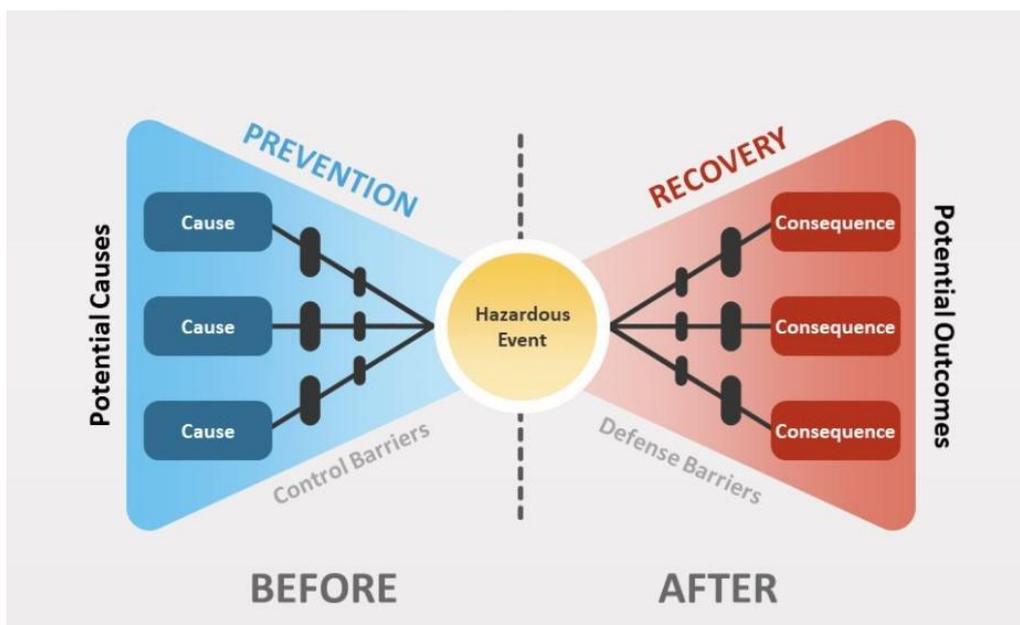
5.3.1 Paving The Way Towards Growing Quantities of Ammonia

Some key concerns which are eminently influencing the energy transition when it comes to ammonia as a hydrogen carrier, decarbonized fuel etc. are listed below:

- Growing volumes of liquid ammonia are being produced / transferred and stored to facilitate the transition away from fossil-based hydrocarbons.
- In densely populated EU regions (highly urbanized space constraint regions) large clouds of gaseous ammonia may be released with disastrous consequences for the people.
- This potentially causes an increase in external (environmental) safety by simple way of statistics.
- Public perception is a tough nut to crack, noting society feels industry is contradictory, creating more risk against the general tendency of reducing risks, preferably to zero.
- All (chemical) substances in high volumes do generate certain risks, from fossil-based hydrocarbons to hydrogen to ammonia and other chemicals. Fossil based hydrocarbons do run the world, however, have also caused major releases into the environment with severe consequences. Lessons learned have been implemented along the way to make the industry safer to the point where we are now. Example: would fossil hydrocarbons have been introduced and usage thereof increased dramatically if we knew up front what the climate (change) risk involved would be? Still, it is widely accepted and economically embedded in all our activities.
- Ammonia, methanol and hydrogen, as new sources of clean energy, being less known to the population, might be seen to be more dangerous, although these fuels will reduce the climate risks

Looking at the above, the opposite is the case; with the experience of today's ammonia production and handling technologies as well as improved measuring and inspection possibilities, the safety in handling ammonia has only improved towards the highest standards, using more than 100 years of experience. The Best Available Technologies (BAT) technologies currently available and proposed to be used shall guarantee the best way towards a safer and more climate friendly fuel economy. Mechanical or more importantly, operation and handling human errors might not be 100% avoidable however, applying BAT allowing for intrinsically fail-safe installations and improved operational procedures these human factor-based failures can be significantly minimised, reducing the holes in a so-called bow-tie approach for safe operation and handling of one's bulk hazardous chemical facilities (refer to Figure 5-9).

Figure 5-9 Bow-tie approach on safety



A Dutch Example of co-partnership

In Netherlands, the PGS-12: Ammonia Storage and Offloading, is the Dutch guideline for the safe storage and handling of ammonia. PGS-12 does not only oversee the design of new tanks but also the retrofitting of existing (LPG)-tank to store ammonia. Currently it is being updated with close collaboration between the private and the public sector. The update is currently in its finalization stage readily implemented and enforced by the regulators.

Important new aspects introduced are:

- 3-wall approach for storage tanks: steel-steel-concrete; single or double roof, both allowed for storage tanks
- In-tank pumps
- ESD-systems for loading vessels, trucks and rail cars
- Flare or scrubber (depending on the site situation)
- Potential integration with ammonia cracker facilities

The remainder of the updates in the PGS-12 concerns allowance for larger volumes to be handled and implementation of lessons learned from past mistakes in operating, maintenance and inspection regimes assuring coverage of the latest standards.

Summarizing, this PGS-12 updating process is a true example towards a safer and cleaner future and could be chosen in many other parts of the world as a benchmark for local governments being lesser aware of how the ammonia industry would affect their region. In any case, alignment and general acceptance of international established standards around the globe is the only way to facilitate the development of the ammonia market.

5.3.2 Ammonia Handling in Loading and Unloading Facilities

Loading lines for RTCs and trucks are relatively small with loading rates in the 20-50 t/h range, filling a RTC or truck in maximum 1 hour. Sprinkler installations, ESD valves, loading arms with correct connections and automatic shutdown systems, shall minimize the external safety related releases. Still operators and people at the site are close by and should be prepared for emergency responses concerning themselves or their colleagues, since every connection contains a potential risk. This frequency of loading RTCs and trucks does correlate to the phenomenon that most of the incidents concerning ammonia have been seen in the loading and unloading of RTCs and trucks.

The ammonia loading arms used to fill RTCs and trucks are like those used for shipping. Swivel joints are used to connect rigid piping, allowing for easy manoeuvrability in both horizontal and vertical axis. A main valve is essential for shutting off the product flow in the loading arm, while the nitrogen purge connection enables tank purging (Kanon, 2023). Different types of couplings are employed, including screw couplings, flange-type couplings, and dry break couplings. Among these, the first two are the most used methods (EFMA, 2008). Generally, it is crucial to ensure that the couplings on the RTC or the truck and the loading/unloading arm are perfectly compatible in terms of design to prevent any leakage during the transfer of the product. Therefore, compatibility with the fixed installations should be verified before dispatch of cargo. If necessary, a suitable adapter can be potentially used to ensure a proper connection.

5.3.3 Country Focus

The main laws / regulations in place for the countries of interest were covered in the Section SO1 - General Overview of the Green Ammonia Value Chain as well as in SO3 - Ammonia Transport. Therefore, only additional regulation related exclusively to storage will be presented. Some additional standards / remarks are stated below

API 620/625 Design and Construction of Large, Welded, Low pressure Storage Tanks

- Appendix R: specific requirements for temperatures down to -52,5 °C
- Appendix Q: specific requirements for temperatures down to -167 °C

DIN 4119 and BS 7777

- Allow lower thickness for the shell plates
- Higher requirements on the steel quality

EEMUA 147 (1986-2016): Recommendations for refrigerated liquefied gas storage tanks

EN 14620: applicable as from 2007 in the EU

- Part 1: general
- Part 2: metallic components
- Part 3: concrete components
- Part 4: insulation components
- Part 5: testing, drying, purging and cool-down
- Pending Part 6 (liquid oxygen, liquid nitrogen or liquid argon)
- Pending Part 7 (liquid ammonia, expected 2025)

5.3.3.1 Chile

Storage of hazardous substances is regulated through Executive Order N° 43. which was adopted in 2015 from the Ministry of Health. The definition of hazardous substances is defined in standard NCh 382:2013 and identified in accordance with standard NCh 2190:2003. Additionally, the NCh N 2245:2015, regarding the Product Safety Data Sheet is mentioned.

5.3.3.2 Germany

Focused on storage are the following also partly mentioned above:

- VDI RL 3783: For the calculation of gas dispersion
- Commission for Plant Safety KAS-18: Recommendation on safety distances
- VDI RL 3783: For the calculation of gas dispersion
- DIN EN 14620: Design and manufacture of site-built, upright, cylindrical flat-bottom steel tanks for the storage of cryogenic liquefied gases at operating temperatures between 0 °C and -165 °C.
- EN 1252-1 Cryogenic vessels - Materials - Part 1: Toughness requirements at temperatures below - 80 °C
- VDI RL 229: Emission reduction - Test criteria for the monitoring of vapor recovery systems
- AwSV: Ordinance on the Handling of Substances Hazardous to Water in Stationary Applications

5.3.3.3 USA

In the USA the 1910.111 - Storage and handling of anhydrous ammonia is in place.

5.3.3.4 Australia

In terms of design standards, as mentioned, Australia has some country specific codes. The AS/NZS 2022:2003, titled "Storage and Handling of Anhydrous Ammonia," covers various aspects related to the safe storage and handling of anhydrous ammonia, including among others:

- Design and Construction
- Location and Safety Measures

- Operation and Testing
- Emergency Management
- Fire Protection

An example where this legislation would be considered applicable would be for instance in Yara’s Pilbara Fertilizer Plant, one of the largest ammonia productions sites worldwide.

5.4 Cost Estimate for Ammonia Storage at Large Scale

5.4.1 Scenario Definition

The focus of the current report is on large scale ammonia installations that would enable the transition to a decarbonized economy. As explained in 5.2.2, for large scale storage, the fully refrigerated concept is the industry practise. Consequently, the scenario which will be evaluated is the following:

Table 5-3 Storage scenario for cost estimate development

Storage Technology	Single Tank size (kt)	Number of Tanks	Aggregate Capacity (kt)
Fully Refrigerated	45	2	90

5.4.2 Cost Estimate Class 5

For such a storage capacity at fully refrigerated conditions, according to industry insights, the CAPEX is 125 million USD with a cost accuracy of AACE Class “V”. The cost estimate is inclusive of the following:

- Installation
- Tank
- Refrigeration system
- Flare
- Pumping system
- Loading arm
- Utilities
- I&C system
- Electrical system
- Control room
- Contingency

Some major cost components such as permitting, owners’ costs, jetty infrastructure and utilities interconnection as of 100 m from site are not included.

In general, the construction cost of an ammonia storage facility, even for the same storage capacity, can vary significantly between various locations, as it is influenced by factors such as:

- Site conditions (ambient conditions, seismicity, geotechnical conditions)
- Logistics and components transport complexity
- Labour costs
- Material costs
- Engineering complexity
- etc.

5.5 RWE Context - Ammonia Storage

When sizing storages for the transport of ammonia, two rules of thumb are typically applied to ensure a cost competitive design of the storage facilities, sizing based on delayed vessel arrival or sizing based on yearly throughput,

In the case of a storage “sizing based on a delayed vessel arrival”, the largest foreseen vessel capacity is considered as minimum storage capacity. Furthermore, a storage capacity in the range of 6 to 15 days is added to ensure adequate flexibility to cope with irregularities in the arrival of the vessels such as bad weather, damages, or short-term unavailability’s of vessels in the market. The size of buffer capacity (typically 6 to 15 days) is mainly defined by several project / port specific constraints:

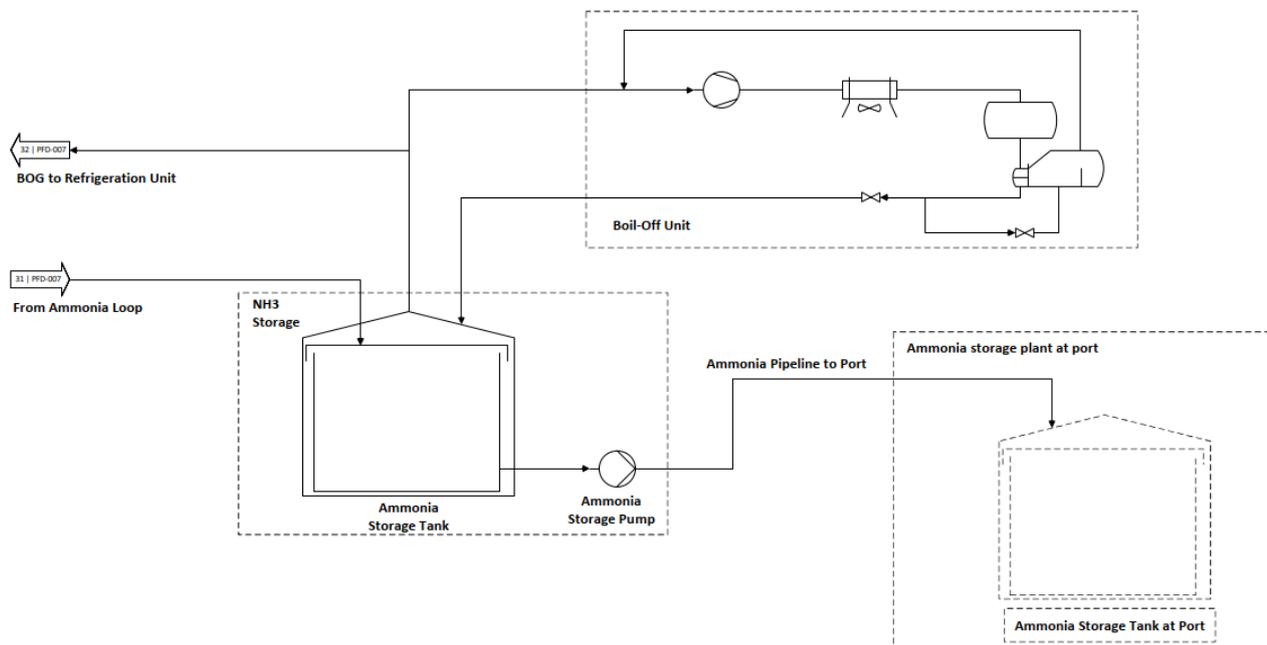
- Port accessibility (how likely is a port entry denied due to bad weather)
- Type of shipping contract (who owns the ship, and which penalties apply in case of delayed arrivals)
- Transport distance (the longer the distance, the more possible delays are)

In the case of a storage “sizing based on yearly throughput”, the yearly throughput capacity and a factor for the storage sizing (6,25%) is used to estimate the required storage capacity. This rule of thumb enables an initial storage sizing, when no further limitations (e.g., vessel information, number of offtake destinations) are known, as it tries to also include a cost optimization approach to design the vessel capacity. This means that ideally only 5% of the yearly capacity should be transported via one vessel.

RWE will not have ownership of facilities in the reference export port, Puerto Sara. Instead, RWE will solely lease export capacity. Considering this fact, a single storage facility at the synthesis plant in Villa Tehuelches was selected. Following the “sizing based on yearly throughput” approach mentioned earlier, the onsite ammonia storage capacity will be 39,000 m³.

The Process Flow Diagram (PFD) of the storage tank with its relevant components is presented in Figure 5-10.

Figure 5-10 Process Flow Diagram of the ammonia storage tank in the NH₃ synthesis plant



The ammonia storage tank is designed to withstand the low temperature of the liquid ammonia and as such, has to be properly insulated. However, as already explained, the creation of some BOG is inevitable. This gas is removed from the tank to prevent pressure buildup and is directed to either the refrigeration unit of the Haber Bosch or the boil-off gas unit to be reliquefied (redundant concept). The ammonia being stored in the synthesis plant is pumped via a pipeline to the storage premises of the Puerto Sara port.

6 Conclusions and Recommendations

The ammonia market has long been a thriving industry, reaching the production of 186 million tons in 2020. However, as the global population continues to grow and affluence rises, there is an urgent need for even more ammonia. Yet, this increasing demand comes at a time when governments worldwide are targeting to achieving net-zero emissions in the energy sector. This puts pressure on finding sustainable solutions that meet the growing ammonia demand, while simultaneously minimizing environmental impact.

To realize this ambitious undertaking and move to a green ammonia value chain, a multitude of steps is necessary:

1. **Governments:** Regulation has a pivotal role to play in shaping a sustainable and low-emission future. The current slow-down in green ammonia project development can be attributed to the lack of a clear business case for producers. For consumers, carbon-emitting alternatives are still cheaper than green ammonia and a framework to cover the cost difference does not exist. Hence, the general market framework is still such that using green ammonia is not attractive to consumers. Mechanisms such as Germany's H2Global's auction for green ammonia or Japan's JERA auctions for low carbon ammonia have provided tangible results for some projects. These are, however, limited quantities. A reliable pathway towards a framework enabling a green ammonia market is still under development, causing uncertainty for project developers and hence investment decisions are not taken. Developing a playing field that gives green ammonia project developers a clear business case is therefore the key task for governments in enabling the market ramp-up.
2. **Research and Development:** The individual technologies of the upstream block of the ammonia value chain, i.e., electrolysis and ammonia synthesis, have existed since decades. For example, alkaline electrolysis is entirely mature, having a TRL of 9, where the same applies to ASU and ammonia synthesis facilities. The novelty is found in the combination of these technologies at scale, combining intermittency (RES) with normally considered steady state processes (ammonia synthesis). The deployment of large-scale green ammonia plants can be expected to result in a significant learning curve regarding the dynamic behavior of the process components and their interaction. Since large-scale green ammonia projects are first-of-its-kind plants, collaborative projects and partnerships are key to fostering needed development and risk mitigation. Lastly, accumulating knowledge through smaller sized projects as well as decentralized applications, can pave the way towards the desired up-scaling of the PtX plants.
3. **Infrastructure Development:** The ammonia industry benefits from its extensive infrastructure that spans across all aspects of the value chain, including production, transportation, storage, and handling. With this solid foundation, the industry is well-prepared to expand its infrastructure to cater to the increasing demands of the future. Nonetheless, one area of focus for the industry should be the ammonia cracking, a process required to facilitate the usage of green ammonia as a hydrogen carrier. While various OEMs are currently intensively researching decarbonized ammonia cracking, the technology is not yet ready for large-scale commercial use and therefore, further advancements are needed. Moreover, due to the large scale and costly nature of infrastructure projects such as ammonia import/export terminals and long pipeline systems, public financing mechanisms and support will be required. Lastly, in locations where multiple green ammonia production projects are being realized, the concept of shared infrastructure should be considered. By sharing resources and facilities, the costs can be distributed amongst the projects, making them more economically viable. Besides, this approach allows for the benefits of economy of scale, achieving greater efficiencies and cost savings.
4. **Safety:** Ammonia has been handled as a chemical substance for more than a century, and this experience has resulted in a high level of safety and technical efficiency. In fact, the handling of ammonia has consistently improved in terms of safety. Technological advancements have enhanced measuring and inspection capabilities, while lessons learned have been applied to bring the industry to its present state. However, ammonia, as well as other decarbonized fuels like methanol and

hydrogen, being less known to the population, might be seen to be more dangerous. This is also evident in the cautious approach taken by some import / export ports when it comes to developing ammonia infrastructure, stemming from environmental and safety concerns.

5. Certification schemes: Such schemes play a crucial role in advancing the development of decarbonized fuels, including green ammonia. Many countries, whether acting as exporters or importers, are actively working on establishing certification frameworks to ensure a level playing field for all stakeholders involved. These schemes provide proof that specific methodologies and analytical frameworks are being followed in accordance with defined standards and requirements. As a result, credibility and transparency are established, and consumers can be assured that a certified product or service meets their expectations. Of course, there is a need of harmonization and mutual recognitions of those schemes to enable the free flow of decarbonized fuels across borders and avoid market barriers that hinder the ammonia trade.
6. International Collaboration: Collaboration between technology providers, industries, and research institutions is crucial for sharing knowledge, implementing best practices, and driving the widespread adoption of green ammonia technologies worldwide. Given the nature of this emerging market, it is essential for both importing and exporting countries to form international partnerships that will facilitate the trade.

7 Annex

7.1 List of Assumptions for the Cost Estimates Class 5

7.1.1 International Export of Ammonia Scenario

To populate the ammonia transport scenario from Chile to Netherlands via shipping, various assumptions were made, as summarized in Table 7-1

Table 7-1 Assumptions used in the ammonia shipping cost estimation scenario

Assumption	Value	Unit
Type of Ship	40,100 / 60,000	t / m ³
Charter rate for ship per day	29,000	USD
Ballast Share ³⁰	29,000	USD
Heavy Fuel Oil (grey)	660	USD per tonne
Marine Gas Oil (grey)	990	USD per tonne
Ammonia Price	1,000	USD per tonne
Canal Fees	No canal passage assumed	-

7.1.2 Inland Transport of Ammonia Scenario

The inland transport scenario compared ammonia transport via pipeline and via rail. The considered assumptions are summarized in Table 7-2 and Table 7-3, respectively.

Table 7-2 Assumptions used in the ammonia pipeline transport cost estimation scenario

Item	Value	Unit
NH ₃ Cost	1,000	USD per tonne
Pipeline Nominal Diameter	250	mm
Electricity Cost in Chile	0.11	USD per kWh
Pipeline Lifetime	40	years
WACC	10	%
BOG Loses	0.1	% per 1,000km of pipeline
Full Load Hours	7,000	hours
CAPEX Pipeline per km	1.1	Mi Euro per km
Fixed OPEX	1%	Mi USD per year

³⁰ How much of the whole round trip (incl. return journey) do you need to pay.

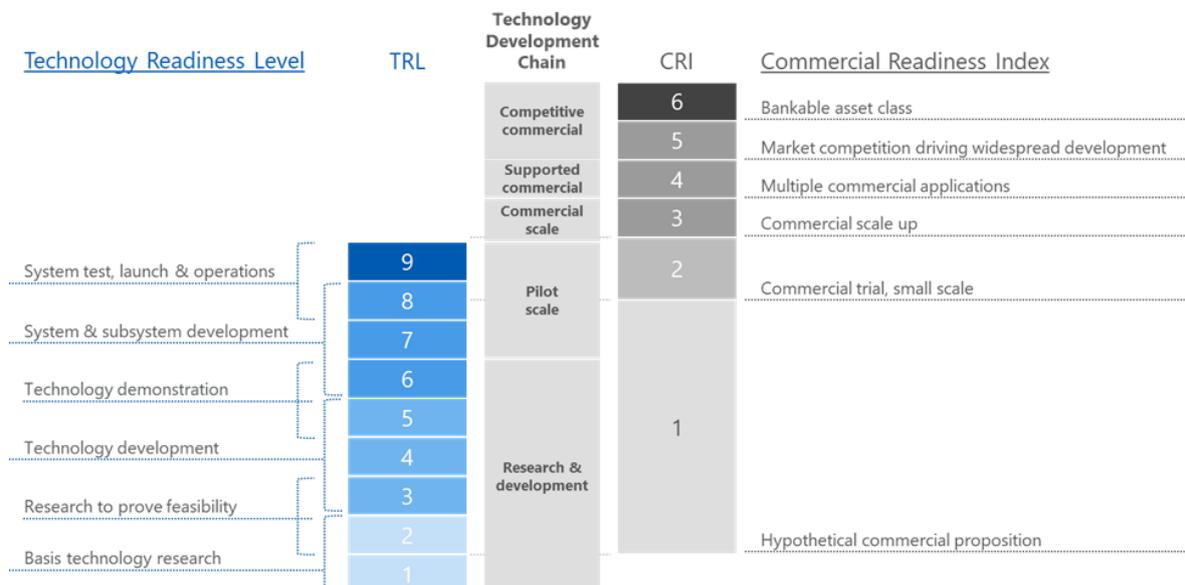
Table 7-3 Assumptions used in the ammonia railway transport cost estimation scenario

Category	Item	Value	Unit
NH₃ Conditions	Storage Temperature	15	°C
	Storage Pressure	16	bar _g
	Average Storage Density	618	kg/m ³
Wagon and Locomotive	Transport Capacity per Wagon	106	m ³
	Filling Rate per Wagon	75	%
	Transport Capacity per Wagon	49,169	kg
	Number of Trips	365	per year
	Transport Capacity per Trip	2,740	tonnes
	Wagons per Trip	56	-
	Number of Diesel Locomotives	2	-
	Number Wagons per Locomotive	28	-
Financial Aspects	Capex Leasing per Locomotive	20,000	USD per month
	Capex per Wagon	200,000	USD
	WACC	10	%
	Diesel Price	1.7	USD per liter
	Capex per Filling Pump	150,000	USD

7.2 Technical and Commercial Readiness

To ensure financing of any project it is important to assess the Technical Readiness Level (TRL) as well as the Commercial Readiness Index (CRI) of the proposed. Figure 7-1 shows how TRL and CRI are interlinked (Arena, 2014). Banks have a very strong focus on towards the CRI. Project funding is more oriented towards the TRL as new and promising technologies should be supported.

Figure 7-1 Technical and commercial readiness level/index (Arena, 2014).



7.3 Certification Schemes Links

To ease the navigation of the reader a table with the relevant links for the certification schemes described in Section 2.3 is included below.

Table 7-4 Certification schemes for decarbonized fuels and relevant links

Country	Name	Link
Australia	Guarantee of Origin certificate scheme	Guarantee of Origin Clean Energy Regulator (cer.gov.au)
Canada	Clean Hydrogen Investment Tax Credit	Archived - Chapter 3: A Made-In-Canada Plan: Affordable Energy, Good Jobs, and a Growing Clean Economy Budget 2023
Denmark	Guarantee of Origin certificate scheme	Nu er det muligt at handle og markedsføre brint som grøn energi Energistyrelsen (ens.dk)
European Union	Renewable Energy Directive II	Commission sets out rules for renewable hydrogen (europa.eu)
France	France Ordinance No. 2021-167	Ordonnance n° 2021-167 du 17 février 2021 relative à l'hydrogène - Légifrance (legifrance.gouv.fr)
Japan	Basic Hydrogen Strategy	20230606_2.pdf (meti.go.jp)
Korea	Clean Hydrogen Certification Mechanism	S Korea outlines clean hydrogen certification system Latest Market News (argusmedia.com)
India	Green Hydrogen Standard for India	Ministry of New and Renewable Energy Ministry of New and Renewable Energy India (mnre.gov.in)
Italy	Guarantee of Origin certificate scheme	Decreto del Ministro n. 224 del 14 luglio 2023 recante "Attuazione dell'articolo 46 del decreto legislativo 8 novembre 2021, n.199 in materia di garanzie di origine" Ministero dell'Ambiente e della Sicurezza Energetica (mase.gov.it)
Netherlands	Guarantee of Origin certificate scheme	Projects Hyxchange
Spain	Guarantee of Origin certificate scheme	Guarantees of Origin - General Information - Enagás (enagas.es)
United Kingdom	Low Carbon Hydrogen Standard: Certification Scheme	UK Low Carbon Hydrogen Standard - GOV.UK (www.gov.uk)
United Kingdom	Renewable Transport Fuel Obligation	Studie (weltenergieerat.de)
United States	Clean Hydrogen Production Standard: Tax Credit	U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Guidance

7.4 Safety Regulations / Schemes / Guidelines Links

Some links for publicly available safety-related documents are presented in Table 7-5 to enable the easier navigation of the reader to the safety topics.

Table 7-5 Links for publicly available safety regulations / schemes /guidelines

Safety Regulation / Scheme	Link
SEVESO III (EU)	Directive - 2012/18 - EN - Seveso III - EUR-Lex (europa.eu)
OSHA 3132 Process Safety Management (USA)	7767-OSHA 3132
Codes of practice for work health and safety (Australia)	Codes of practice for work health and safety Business Queensland
Environment Protection and Biodiversity Conservation Act 1999 (Australia)	cms_nlp_aus_epbc_act_2_1999.pdf
Guide to the Work and Safety Act	guide-to-the-model-whs-act.pdf (safeworkaustralia.gov.au)
Industrial Safety and Health Act (Act No. 57 of 1972) (Japan)	<5461726F2D984A93AD88C09153897190B696402889702081434832302E352E> (cas.go.jp)
CSCL - Chemical Substances Control Law (Japan)	What is CSCL(Chemical Substances Control Law) (METI)

8 Bibliography of the Study

- Amandine, R. D., & Cameron, B. (2024). *How mining could ignite Australia's hydrogen boom*. Institute for Energy Economics and Financial Analysis.
- Arai, K. (2020). Development of 300 kW Ammonia Combustion Micro Gas Turbine. *Journal of Gas Turbine Society of Japan*, 234–239.
- ARAX CHEMISTRY. (2023, January 10). *ARAX CHEMISTRY*. Retrieved from <https://araxchemi.com/en/uses-of-ammonia/>
- Arena. (2014). *Commercial Readiness Index for Renewable Energy Sectors*. Australian Renewable Energy Agency.
- ASHRAE. (2017). *Ammonia as a Refrigerant*. American Society of Heating Refrigeration and Air-Conditioning Engineer.
- Barthers, J. R. (2008). *A feasibility study of implementing an Ammonia Economy*. Iowa: Iowa State University.
- Basset Mechanical. (2024, April 16). *Basset Mechanical*. Retrieved from Basset Mechanical: <https://www.bassetmechanical.com/news/why-use-ammonia-as-a-refrigerant/>
- Blenkey, N. (2021, January 18). *Marinelog*. Retrieved from <https://www.marinelog.com/news/solid-oxide-fuel-cells-could-play-big-role-in-shipping-decarbonization/>
- Breiki, B. (2021). *Comparative life cycle assessment of sustainable energy carriers including production, storage, overseas transport and utilization*. *Journal of Cleaner Production*.
- Brown, T. (2019, January 25). *MAN Energy Solutions: an ammonia engine for the maritime sector*. Retrieved from <https://ammoniaenergy.org/articles/man-energy-solutions-an-ammonia-engine-for-the-maritime-sector/>
- COAG Energy Council Hydrogen Working Group. (2019). *Australia's National Hydrogen Strategy*. COAG Energy Council Hydrogen .
- Crolius, S. (2019, July 18). The Evolving Context of Ammonia-Coal Co-Firing.
- DCCEEW. (2023). Activity Table 1990-2021 - Industrial Processes. Department of Climate Change, Energy, the Environment and Water.
- EFMA. (2008). *Guidance for Transporting Ammonia via Rail*. Belgium: European Fertilizer Manufacturers Association.
- Elishav, Mosevitzky, Medina, & Grader. (2021). Storage and distribution of ammonia. In A. V. Medina, & R. B. Cantara, *Techno-Economic Challenges of Green Ammonia as an Energy Vector*. London: Elsevier.
- EPA. (2016). *EPA Chemical Data Reporting*. Environmental Protection Agency.
- EPA. (2022). *Anhydrous Ammonia Supply Chain – Executive Summary*. Environmental Protection Agency.

- European Maritime Safety Agency. (2023). *Potential of Ammonia as Fuel in Shipping*. European Maritime Safety Agency.
- Fertilizers Europe. (2008). *What is ammonia stress corrosion cracking*.
- Fertilizers Europe. (2009). *Guidance for inspection of and leak detection in liquid ammonia pipelines*. Fertilizers Europe.
- Fertilizers Europe. (2014). *Guidance for Inspection of atmospheric, refrigerated ammonia storage tanks*.
- Fluor. (2023). *Executive Summary of pre-feasibility study by Fluor for: Large Scale Industrial Ammonia Cracking Plant*.
- Galluci, M. (2021). Why the shipping industry is betting big on ammonia. *The ammonia solution*.
- Hassan, C. (2009). *Quantitative risk assessment for the transport of ammonia by rail*.
- Hatfield, O. (2020). *Review of global ammonia supply*. Argus Media.
- Hignett, T. (1985). *Transportation and storage of ammonia - Fertilizer Manual*. Springer Netherlands.
- Huberlich, T., & Schlichthärle, G. (1983). *Tank-car loading station for liquid and aqueous ammonia. A detailed description of the functions and safeguards of a modern, computer-controlled rail-car loading station for liquid and aqueous ammonia*.
- IEA. (n.d.). Retrieved from International Energy Association: <https://www.iea.org/energy-system/low-emission-fuels/electrolysers>
- IEA. (2019). *The future of Hydrogen - Seizing today's opportunities - Report prepared by the IEA for the G20, Japan*. International Energy Agency.
- IEA. (2019). *The Future of hydrogen: Seizing today's opportunity*. International Energy Agency.
- IEA. (2021). *Ammonia Technology Roadmap - Towards more sustainable nitrogen fertiliser production*. International Energy Agency.
- IEA. (2023). *Global Hydrogen Overview*. International Energy Agency.
- IEA. (2023). *Towards hydrogen definitions based on their emissions intensity*. International Energy Agency.
- IEA. (October 2021). *Ammonia Technology Roadmap - Towards more sustainable nitrogen fertiliser production*. International Energy Agency.
- IFA. (1997). *The Haber-Bosch Heritage: The Ammonia Production Technology*. Sevilla: IFA.
- IFA. (2024). *World Ammonia Statistics by Region*. International Fertilizer Association.
- IFA. (n.d.). Production & Trade Tables by Region. 2023: International Fertilizer Association.
- IMO. (2021). *Fourth IMO Greenhouse Gas Study*. London: International Maritime Organization.
- International Fertilizer Development Center. (1998). *Fertilizer manual*. United Nations.

- IRENA & AEM. (2022). *Innovation Outlook: Renewable Ammonia*. Brooklyn: International Renewable Energy Agency.
- IRENA. (2022). *Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward*, International Renewable Energy Agency, Abu Dhabi. Irena.
- Ito, S., Uchida, M., & Suda, T. (2019). Demonstration Test of Ammonia/Natural Gas Co-Firing Power Generation with 2MW class Gas Turbine. *Journal of the Combustion Society of Japan*.
- Jeffrey Ralph Bartels . (2008). *A feasibility study of implementing an Ammonia Economy*. Iowa: Iowa State University .
- John L. Sorrels. (2019). *Selective Catalytic Reduction*. U.S. Environmental Protection Agency.
- Kanon. (2023). *Land Equipment_Bottom and top loading* . Kanon.
- Kanon. (2023). *Marine Loading Arms_Engineered for Generations_Brochure*.
- Kanon. (2024). *Kanon Loading Equipment*. Retrieved from Bottom Loading Arm: <https://kanon.nl/product/land-equipment/bottom-loading-arm/?p=tab-panel-3-2>
- Kiane, d. (2024). *Worldwide greenhouse gas emissions of green hydrogen production and transport*. Nature Energy.
- Larsen & Turbo. (2023, June 1). *Larsen & Turbo*. Retrieved from L&T Construction is all set to create Renewable Energy Infrastructure for the World's Largest Green Hydrogen plant at NEOM: <https://www.larsentoubro.com/pressreleases/2023/2023-06-01-lt-construction-is-all-set-to-create-renewable-energy-infrastructure-for-the-world-s-largest-green-hydrogen-plant-at-neom/>
- Made in China*. (n.d.). Retrieved from T50 LPG/Ammonia/Cryogenic Storage Tank ISO Tank Shipping Container: <https://hnlxtruck.en.made-in-china.com/product/mOZtluvdCRTP/China-T50-LPG-Ammonia-Cryogenic-Storage-Tank-ISO-Tank-Shipping-Container.html>
- McKinsey and Company. (2020). *Chilean Hydrogen Pathway*. McKinsey and Company.
- Michelle Nichols, N. H. (2023). Explainer: Why would pipeline damage threaten Black Sea grain deal? *Reuters*.
- Ministry of Energy, Government of Chile. (2021). *Chile's Green Hydrogen Strategy and Investment Opportunities*. Santiago, Chile: Ministry of Energy, Government of Chile.
- Mitsubishi Power. (2021, March 1). Mitsubishi Power Commences Development of World's First Ammonia-fired 40MW Class Gas Turbine System. Retrieved from <https://power.mhi.com/news/20210301.html>
- MPA Singaport, Fortesque. (2024). *World's First Use of Ammonia as a Marine Fuel in a Dual-Fuelled Ammonia-Powered Vessel in the Port of Singapore*. MPA Singaport, Fortesque.
- Mysore Ammonia*. (n.d.). Retrieved from <https://www.mysoreammonia.com/applications/>

- Neom. (2023, May 22). *NEOM*. Retrieved from NEOM GREEN HYDROGEN COMPANY COMPLETES FINANCIAL CLOSE AT A TOTAL INVESTMENT VALUE OF USD 8.4 BILLION IN THE WORLD'S LARGEST CARBON-FREE GREEN HYDROGEN PLANT.
- Quinn, R. (2024, 2 27). *Progressive farmer*. Retrieved from FMCSA: Nurse Tank Safety Advisory: <https://www.dtnpf.com/agriculture/web/ag/crops/article/2024/02/27/safety-agencies-issue-anhydrous-tank>
- Ray Hattenbach . (2012). *Transportation & Delivery of Anhydrous Ammonia Transportation & Delivery of Anhydrous Ammoni*.
- Reuß, M. (2019). A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany. In *Applied Energy* (pp. 483-453).
- Rouwenhorst, K. (2019). *Islanded ammonia power systems: Technology review & conceptual process design*.
- Rouwenhorst, K. (2022, November 11). Production technology updates: from mega-scale to distributed ammonia.
- Rouwenhorst, K. (2023, March 8). *HyEx: ammonia from the Chilean desert*.
- Rouwenhorst, K., Van Der Ham, A., Mul, G., & Kersten, S. (2019). *Islanded ammonia power systems: Technology review & conceptual process design*. Elsevier.
- SEC. (n.d.). *United States Securities and Exchange Commission*. Retrieved from <https://www.sec.gov/Archives/edgar/data/722079/000095012310013697/c56371bdefa14a.htm>
- Sharma, S. (2023, 2 August). *What are the common uses of ammonia?* Retrieved from Jaysos Chemical Industries: <https://ammoniagas.com/common-uses-of-ammonia/>
- Sternberg, A., & Bardow, A. (2015). Power-to-What? – Environmental assessment of energy storage systems. In *Energy and Environmental Science*.
- Sudipta Chatterjee, R. K.-W. (2021). Limitations of Ammonia as a HydrogenEnergy Carrier for the Transportation Sector. *ACS Energy Letters*.
- Tan, F. (2024, March 4). *MAN Energy Solutions to offer ammonia-fuelled ship engines after 2027*. Retrieved from Reuters: <https://www.reuters.com/business/energy/man-energy-solutions-offer-ammonia-fuelled-ship-engines-after-2027-2024-03-04/>
- TB Global Technologies Ltd. (2021). *Marine Loading Arms*.
- TCG. (2018). *Ammonia Production: Recent Advances in Catalyst and Process Technology and Impacts on the Competitive Landscape*. The Catalyst Group.
- TFI. (2005). *Fertilizer's role in agriculture - The safe rail transport of fertlzer*. Washigton: The Fertilizer Institute.
- The Fertilizer Institute. (n.d.). *Anhydrous Ammonia Tank Car Checklist*. Retrieved from Association of the American Railroads: <https://www.tfi.org/wp-content/uploads/2024/01/NARBrochure.pdf>

- The Ministerial Council on Renewable Energy, Hydrogen and Related Issues. (2023). *Basic Hydrogen Strategy*. The Ministerial Council on Renewable Energy, Hydrogen and Related Issues.
- The Royal Society. (2020). *Ammonia: Zero carbon fertiliser, fuel and energy store*.
- U.S. Department of Energy. (2006). *Potential Roles of Ammonia in a Hydrogen Economy - A Study of Issues Related to the Use Ammonia for On-Board Vehicular Hydrogen Storage* .
- Ulmann, F. (2012). Ammonia, 1. Introduction. In F. Ulmann, *Ullmann's Encyclopedia of Industrial Chemistry*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.
- USGS. (2021). *U.S. Geological Survey, Mineral Commodity Summaries*. United States Geological Survey.
- Verband der Chemischen Industry. (2020). *Chemiewirtschaft in Zahlen 2020*. Verband der Chemischen Industry.
- VTG. (n.d.). *Gas rail tank cars for ammonia*. Retrieved from VTG: https://www.vtg.com/fileadmin/VTG/Dokumente/waggon_datenblaetter/Fluessiggas-Kesselwagen-Ammoniak-G86.104D.pdf
- VTG. (n.d.). *VTG*. Retrieved from 20' ISO Gas Tank container: <https://www.vtg.com/20-iso-gas-tank-container>
- Wärtsilä. (2024). *Meet the world's first 4-stroke ammonia solution for marine*. Retrieved from https://www.wartsila.com/marine/wartsila-25-ammonia?utm_source=mcae&utm_medium=custom-redirect&utm_term=marine-power&utm_content=press-release&utm_campaign=mp-2023-11-virtual-event-ammonia-w25
- William Alden. (1999, November 29). *Flickr*. Retrieved from https://www.flickr.com/photos/bill_alden/21266814494/in/photostream/
- Yuka Obayashi. (2024). *JERA ends ammonia co-firing trial at coal power station with positive results*. *Reuters*.
- Zhou, Z. (2010). *CO2 emissions and mitigation potential in China's ammonia industry*. *Energy Policy*.



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