POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Low-Emissions Ammonia in the Energy Transition: A Critical Analysis of Production Pathways and Infrastructure Scalability

TESI DI LAUREA MAGISTRALE IN
ENERGY ENGINEERING-INGEGNERIA ENERGETICA

Author: **Gianfranco Larghi**

Student ID: 952752
Advisor: Paolo Colbertaldo
Academic Year: 2024-25

Abstract

This thesis examines the role of ammonia in the energy transition by combining two complementary perspectives: production-side decarbonisation and infrastructure scalability. Ammonia is a major industrial commodity, but its conventional production is associated with significant greenhouse-gas emissions due to fossil fuel reliance. Decarbonising production is therefore an important mitigation lever even without changes in end uses. At the same time, ammonia is increasingly considered as a low-emissions energy- and hydrogen-carrier, which would require additional volumes and new logistics configurations.

This work develops a 3E analysis of conventional production pathways, assessing energy performance, environmental impacts, and economic aspects. In parallel, it reviews ammonia logistics and safety requirements and proposes a scenario-based critical assessment of infrastructure scalability using global scaling ratios derived from demand trajectories. The findings suggest that grey ammonia remains an important benchmark, while low-emissions pathways do not show uniformly superior outcomes under all conditions. From an environmental perspective, climate-related benefits can be significant, but they do not automatically translate into improvements across all LCA impact categories. Economically, green ammonia remains strongly constrained by electricity costs, whereas blue ammonia appears cost-competitive in the short to medium term. On the infrastructure side, current handling practices are mature but the energy transition will require a significant strengthening of the entire logistics chain.

Debarbonising production pathways is a necessary but not sufficient condition for large-scale deployment. The effective scalability of low-emissions ammonia depends on whether infrastructure network can expand, adapt, and integrate in time to meet new demand. For this reason, ammonia deployment is framed as a system-level implementation challenge in which infrastructure readiness may become the decisive bottleneck. Overall, low-emissions ammonia should not be viewed solely as a production technology, but as a development option whose deployment depends on infrastructure readiness, timing, and coordination among the actors involved.

Key-words: Ammonia, Energy transition, Decarbonisation, 3E analysis, Infrastructure scalability.

Abstract in italiano

Questa tesi analizza il ruolo dell'ammoniaca nella transizione energetica considerando due prospettive complementari: la decarbonizzazione della sua produzione e la scalabilità infrastrutturale. L'ammoniaca è una materia prima industriale di primaria importanza, ma la sua produzione tramite metodi convenzionali è associata a significative emissioni di gas serra dovute alla dipendenza dai combustibili fossili. La decarbonizzazione della produzione rappresenta quindi una leva di mitigazione rilevante anche senza cambiamenti negli usi finali. Allo stesso tempo, l'ammoniaca è sempre più considerata come vettore energetico e di idrogeno a basse emissioni, con conseguente aumento dei volumi e necessità di nuove configurazioni logistiche.

Questo lavoro sviluppa un'analisi 3E dei principali processi produttivi convenzionali di ammoniaca, valutando prestazioni energetiche, impatti ambientali e aspetti economici. In parallelo, esamina i requisiti logistici e di sicurezza e propone una valutazione, basata su scenari, della scalabilità infrastrutturale tramite rapporti di scala globali derivati da traiettorie di domanda. I risultati mostrano che l'ammoniaca grigia rimane uno standard di riferimento importante, mentre i processi a basse emissioni non presentano risultati uniformemente superiori in tutte le condizioni. Dal punto di vista ambientale, i benefici climatici possono essere significativi, ma non si traducono automaticamente in miglioramenti in tutte le categorie di impatto LCA. Sul piano economico, l'ammoniaca verde resta fortemente vincolata ai costi dell'elettricità, mentre l'ammoniaca blu appare competitiva nel breve/medio termine. Sul lato infrastrutturale, le pratiche attuali di gestione sono mature, ma la transizione energetica richiederà un significativo potenziamento dell'intera catena logistica.

Il miglioramento dei processi produttivi è una condizione necessaria ma non sufficiente per una diffusione su larga scala. La scalabilità effettiva dell'ammoniaca a basse emissioni dipende dalla capacità della rete infrastrutturale di espandersi, adattarsi e integrarsi nei tempi richiesti dalla nuova domanda. Per questo motivo, la diffusione dell'ammoniaca viene interpretata come una sfida di implementazione a livello di sistema, nella quale la maturità infrastrutturale può diventare il collo di bottiglia decisivo. Nel complesso, l'ammoniaca a basse emissioni non dovrebbe essere considerata soltanto come una tecnologia di produzione, ma come un'opzione di sviluppo la cui attuazione dipende dalla maturità delle infrastrutture, dalle tempistiche e dal coordinamento tra gli attori coinvolti.

Parole chiave: Ammoniaca, Transizione energetica, Decarbonizzazione, Analisi 3E, Scalabilità infrastrutturale.

Contents

Introduction

Ammonia is one of the most widely produced chemicals worldwide and an essential input product in modern agriculture and in several industrial value chains. Its relevance in the energy transition can be linked to two factors. First, ammonia production today is associated with substantial greenhouse-gas (GHG) emissions, stemming from fossil-based hydrogen supply and energy-intensive synthesis process. Therefore, decarbonising ammonia production can be significant, even without changes in end uses. Second, ammonia is increasingly discussed as an energy and hydrogen carrier, supporting the decarbonisation of additional sectors where direct electrification may be challenging.

However, the role of low-emissions ammonia in the energy-transition context, cannot be inferred from production improvements alone. While decarbonising production is a precondition, the ability to deploy the product at scale is also limited by the readiness of infrastructure and by the feasibility of expanding, adapting, and integrating existing assets to accommodate new volumes and routes. In this sense, the challenge is not purely technological: it is also an implementation and system-integration problem involving industrial logistics and safety constraints. This thesis is grounded in this perspective and frames ammonia deployment as a system-level challenge in which infrastructure readiness can become a decisive bottleneck even when production processes improve.

To support this framing, the thesis develops two complementary lines of analysis. On the production side, a critical 3E assessment of conventional ammonia production pathways is developed, addressing energy performance, environmental consequences, and economic aspects. On the infrastructure side, this thesis reviews the current state of ammonia logistics and safety, and then critically assesses whether global infrastructure can scale in line with demand trajectories provided by IRENA.

Overall, the thesis contributes to a structured interpretation of ammonia's role in the energy transition by linking production-side improvements to infrastructure-side constraints that shape real-world implementation.

1 Ammonia context

This chapter introduces ammonia by summarising its key physico-chemical properties, historical and industrial relevance, global production, trade and market structure, current end-uses, and the main environmental and health implications, before framing why low-carbon ammonia is strategically relevant in the energy transition.

1.1. Ammonia properties

Ammonia (NH_3) is a small, polar, hydrogen-rich molecule, and these fundamental features support its solubility, handling behaviour, and material-compatibility considerations [1]. The spatial molecular structure is provided in Figure 1.

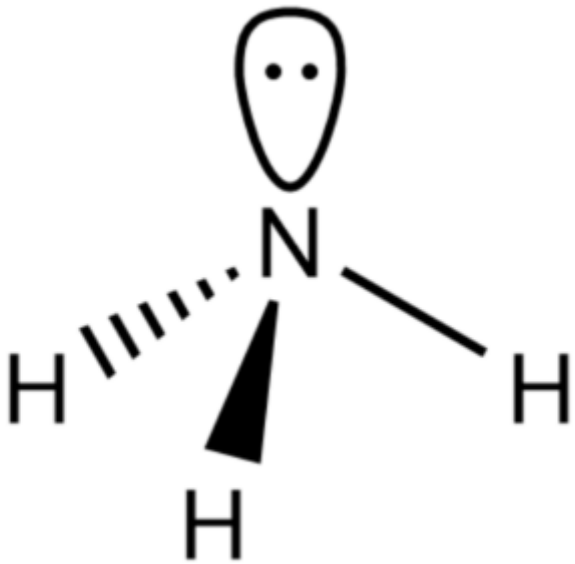

Figure 1 - Ammonia molecular structure [1].

Its polarity makes ammonia an effective hydrogen-bond acceptor, contributing to its high affinity for water and influencing handling and environmental behaviour, though it is not a good hydrogen-bond donor [1].

Under atmospheric temperature and pressure, is a colourless gas with a density lower than air, whereas at atmospheric pressure has a boiling point close to −33.3°C, with a liquid density roughly around 680 kg/m^3, enabling liquefaction under relatively mild conditions compared with other cryogenic fuels, such as hydrogen. When pressure exceeds 8.6 bar at 20 °C, ammonia becomes a liquid with a density of about 610 kg/m^3 [2].

In its pure form, ammonia is referred to as anhydrous ammonia, which is hygroscopic and readily absorbs moisture from the air: when released it can form a dense white cloud due to its affinity for water [2].

Table 1 reports physico-chemical properties commonly used to compare ammonia with other energy carriers.

Table 1 - Physico-chemical properties of ammonia, methanol, hydrogen and methane compiled from [2], [3], [4], [5].

Property	**Ammonia (NH_3)**	**Methanol (CH_3OH)**	**Hydrogen (H_2)**	**Methane (CH_4)**
Hydrogen content (%)	17.7	12.5	100	25.13
Gravimetric energy density (MJ/kg)	18.6	19.7	120.2	50
Volumetric energy density (GJ/m^3)	11.4	15.6	2.1	21.5–23.5
Flammability limits in air (%vol)	15–28	6–36	4–74	5–15
Explosion limits in air (%vol)	16–25	5.5–44	18.3–59	5–15
Boiling point (°C)	− 33	65	− 253	− 161.5
Density (kg/m^3) (liquid conditions)	610 (20°C, 10 bar) 680 (−33°C, 1 bar)	792	70.8	430–470

It can be noted that ammonia's positioning among energy carriers combines moderate mass-specific energy content with comparatively favourable volumetric performance relative to liquid hydrogen. In handling terms, ammonia is less cryogenic than liquid hydrogen or liquid methane, as it can be stored in liquid form at substantially higher temperatures and does not require the extremely low cryogenic conditions typical of those fuels (below −100°C). This is why ammonia is often framed as easier to manage while still enabling compact liquid storage [2].

Ammonia flammability is generally considered a secondary safety concern because ignition is associated with relatively specific conditions, even though it still requires management during storage and use. Accordingly, it is described as harder to ignite than common fuels, with reported ignition parameters showing a higher minimum ignition energy (minimum energy required to ignite a flammable fuel-air mixture) and a higher auto-ignition temperature (minimum temperature at which it ignites spontaneously without an external ignition source) than methane. For reference, methane is reported with a minimum ignition energy of 0.27 mJ and an auto-ignition temperature of 537 °C, whereas ammonia is reported with 8 mJ and 651 °C, supporting the distinction in ignition difficulty [2].

Ammonia is commonly described as burning with difficulty in open air and typically requiring a supporting/pilot flame (an external flame, often from an auxiliary fuel) to sustain combustion; however, in confined spaces it may still present an explosion hazard under certain conditions, especially in the presence of oil contamination, which can increase its flammability [2].

Despite these considerations, toxicity remains the primary safety driver, since hazardous concentrations in air are reached far below the concentrations associated with flammability/explosivity, as also shown in Figure 2.

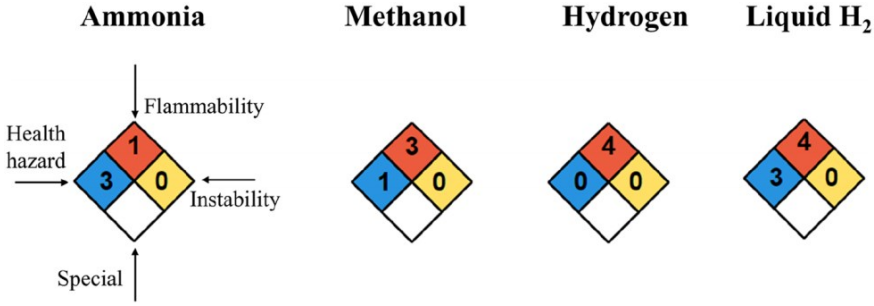

Figure 2 - Fire diamonds of ammonia, methanol, hydrogen and liquid hydrogen [3].

Therefore, the dominant health hazard is linked to ammonia's toxicity in both gas and liquid phases.

Under standard conditions, ammonia can also induce severe corrosion, mostly in the form of Stress Corrosion Cracking (SCC), which is addressed in the infrastructure chapter (Section 0) [3], [6].

Overall, ammonia combines relatively mild liquefaction requirements with distinct safety trade-offs, which motivate the separate hazard discussion in Section 1.5 and support its energy/hydrogen-carrier role in Section 1.6 [2].

1.2. Historical overview and industrial relevance

This section provides a compact historical overview of the Haber-Bosch ammonia synthesis route, focusing on its origin and industrial relevance, while detailed process description is provided in Section 2.1.

The high-pressure ammonia synthesis method that became known as the Haber-Bosch process was developed by Fritz Haber and Carl Bosch in the early twentieth century in response to concerns about nitrogen fertiliser scarcity and the strategic importance of synthetic explosives [6].

The core synthesis reaction is exothermic and reported in Equation (1) [7]:

$$N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)} \qquad \Delta H_f^0 = -92\frac{kJ}{kmol} \tag{1}$$

Industrial implementation required multiple enabling innovations, including reactors able to withstand around 200 bar and the development of an iron-based catalyst promoted with aluminium after extensive experimental screening [6].

BASF built the first industrial Haber–Bosch plant in Oppau (Germany) in 1913, producing nitrogen from air and hydrogen from coal-derived inputs before reacting them at high pressure and temperature over the iron catalyst [6].

Synthetic ammonia-based fertilisers enabled sustained increases in crop yields and supported global population growth (Figure 3 and Figure 4).

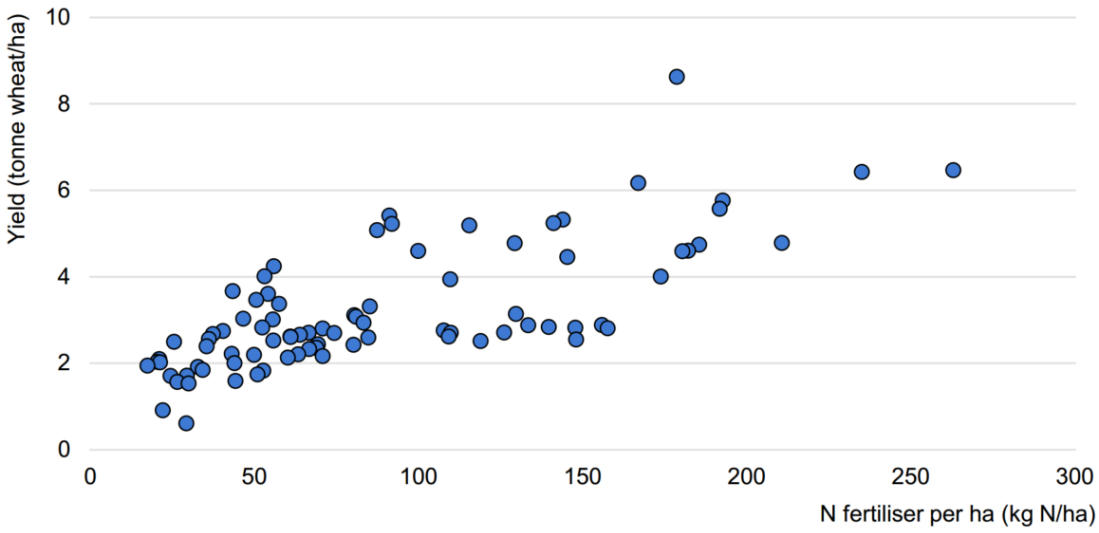

Figure 3 - Relation between fertiliser use and crop yield in wheat production [8].

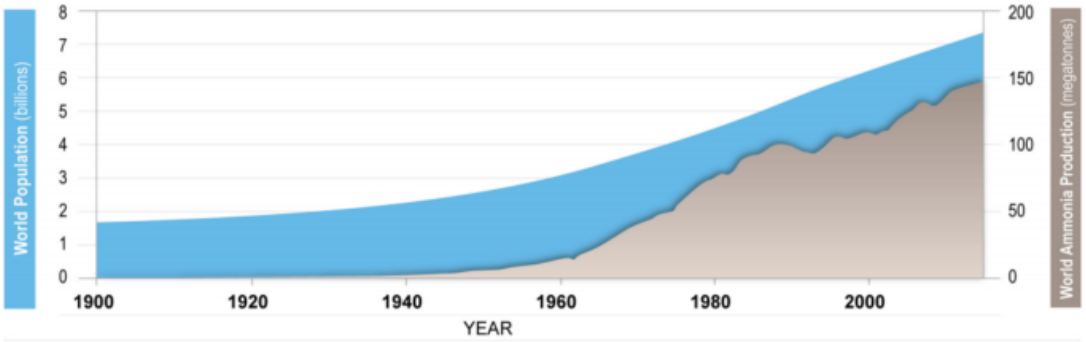

Figure 4 - Growth of global population and synthetic ammonia for fertilisers to support food production [6].

Modern industrial configurations rely on a high-pressure catalytic synthesis loop with recycle, which is described in detail in Section 2.1.

During World War II, large-scale plants using hydrogen from steam reforming of methane/natural gas were constructed in the United States, marking a shift away from coal-based hydrogen routes for several installations. Subsequent twentieth-century industrial improvements cited for reforming-based ammonia plants include the adoption of centrifugal compressors (enabling larger unit sizes), single-stream reactors, and shaped catalysts designed to increase activity while limiting pressure drop [6].

Overall, the historical development of the Haber-Bosch process, established ammonia as a fundamental industrial chemical by enabling scalable conversion of atmospheric nitrogen into reactive nitrogen for fertiliser production. This industrialisation is directly linked to the long-term increase in agricultural productivity and the ability to sustain global population growth [6], [8].

At the same time, the reliance of conventional production on fossil-derived hydrogen has created a significant environmental footprint (See Section 1.5), which motivates the assessment of alternative production routes [9].

1.3. Global production, trade flows and market structure

This section reviews the evolution of global ammonia production and trade, highlighting the geographic concentration of capacity and output, and linking cross-border balances and trade corridors to the way ammonia prices are reported through benchmarks and assessments. It then introduces key pricing conventions and provides a short context on long-term price variability.

Figure 5 introduces the long-term evolution of global ammonia production and trade, showing production rising from about 131 Mt in 2000 to 189 Mt in 2024, corresponding to an increase around 44%.

Across the same period, the traded amount remains consistently smaller, and the relative scale appears broadly stable over time. Therefore, international ammonia trade is reported as a minority share of the overall market, accounting for roughly 10% of the global production [6].

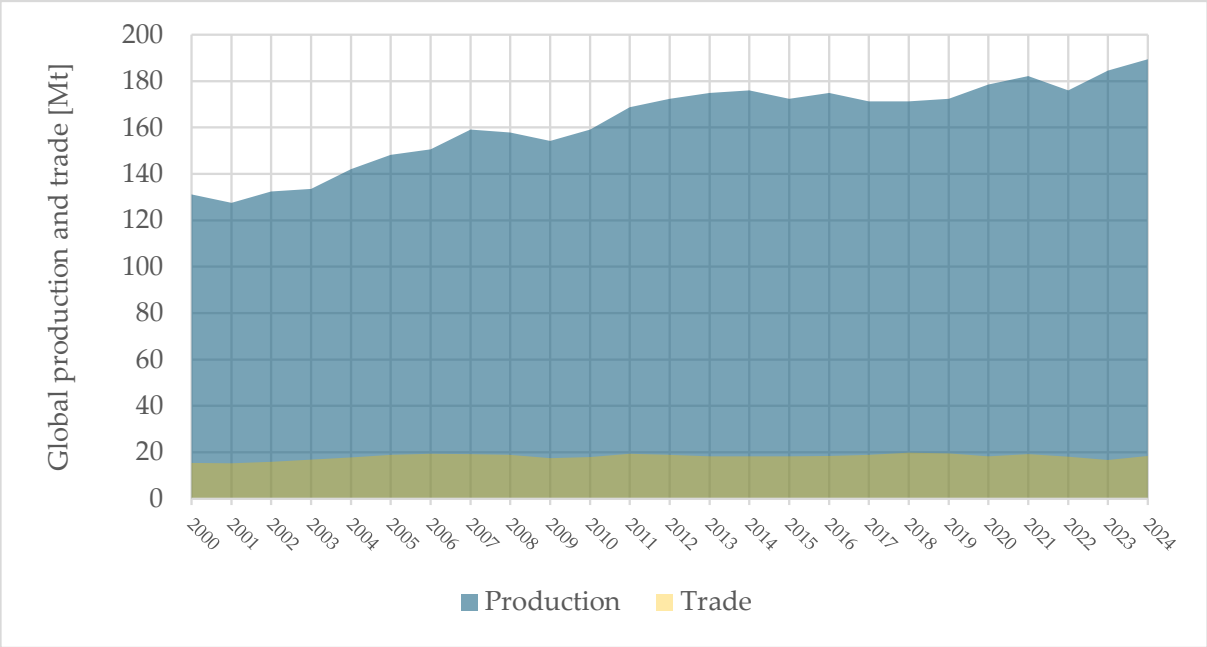

Figure 5 - Global production and trade of ammonia (*), based on [10].

(*) The amount of fixed nitrogen available in the dataset is converted into ammonia using the ratio between molecular masses. For 2024, the traded quantity is not available in the main dataset and is therefore estimated using the midpoint of the reported traded range from an alternative source [11].

The observed production trend is supported by a large installed capacity, exceeding 230 Mt/y in 2020, with a corresponding utilisation rate around 80%, suggesting that

the system operates close to full use in aggregate terms. Since ammonia production relies on the Haber-Bosch process under high temperature and pressure, the economies of scale promote the development of increasingly larger plants: typical capacities for new-built plants in the 2000s reached 2000 t/day, while more recent design can produce up to 3300 t/day [6].

At regional level, production capacity is reported as highly concentrated in Asia, accounting for more than half of the total [9]. Figure 6 translates the global production into a country ranking for 2024, showing China as the largest producer (59.5 Mt), followed by India and Russia (18.2 Mt) and United States (16.5 Mt). The same ranking reveals a second tier of producers, including Indonesia and Saudi Arabia, below the 10 Mt threshold.

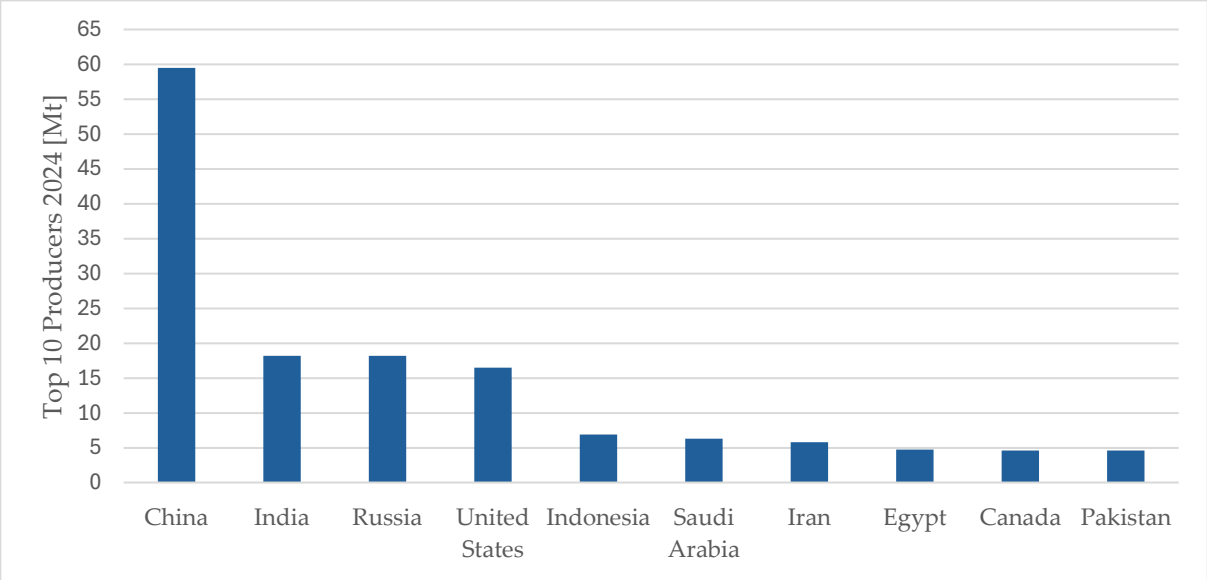

Figure 6 - Top 10 ammonia (*) producing countries in 2024 based on [10].

(*) The amount of fixed nitrogen available in the dataset is converted into ammonia using the ratio between molecular masses.

Figure 7 complements the ranking by showing the percentage breakdown of global production by country, with China at 31%, India and Russia at 10% each, United States at 9%, totaling 60% of the global production, while the rest of the world accounts for 23%.

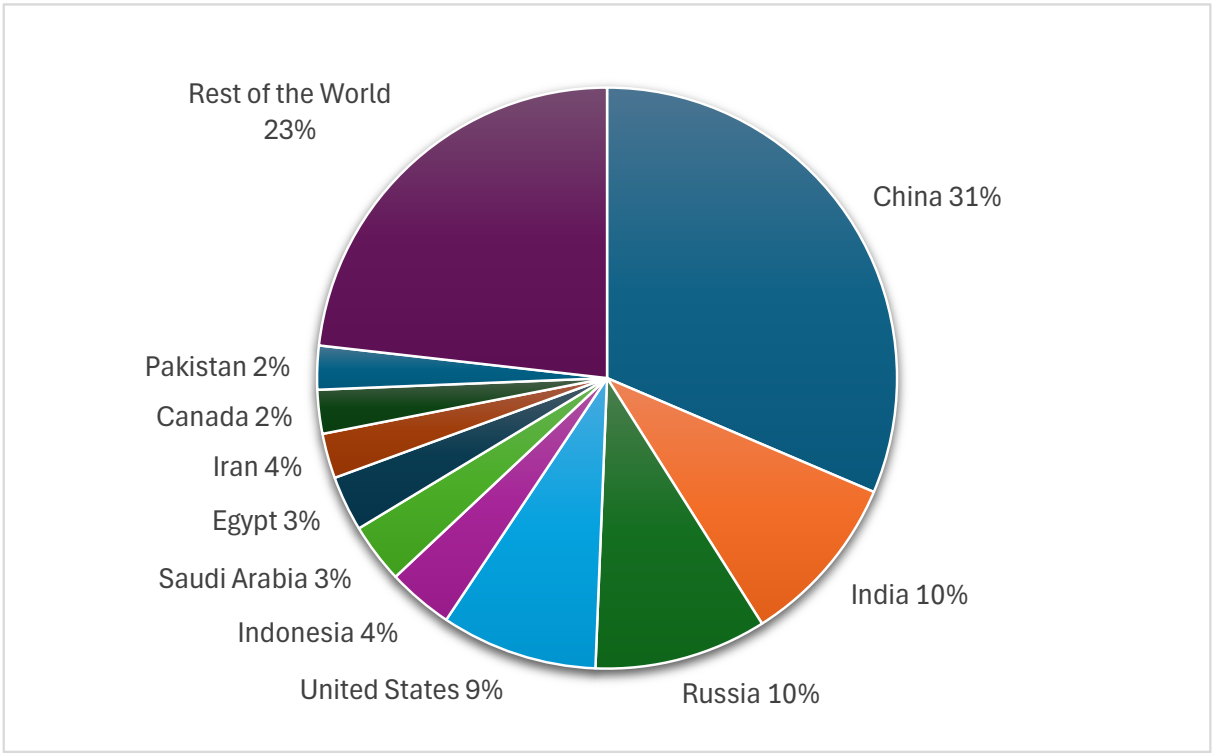

Figure 7 - Share of global ammonia production by country in 2024 based on [10].

On the demand side, the Asia-Pacific region is reported to account for more than half of global consumption, which aligns with the high production levels observed for Asian producers in Figure 6 and Figure 7 [9].

Focusing on countries more exposed to international trade, Figure 8 and Figure 9 clarify the actors supplying the market and those relying on import, reporting the top 10 exporters and importers in 2024, respectively.

Figure 8 shows that Trinidad & Tobago leading the exporters ranking with 2.8 Mt, followed by Saudi Arabia (2.2 Mt) and Indonesia (1.7 Mt), with Canada and United States at roughly 1 Mt each. Since the exporter list includes both large and small producers, the export prominence is not directly proportional to domestic production size.

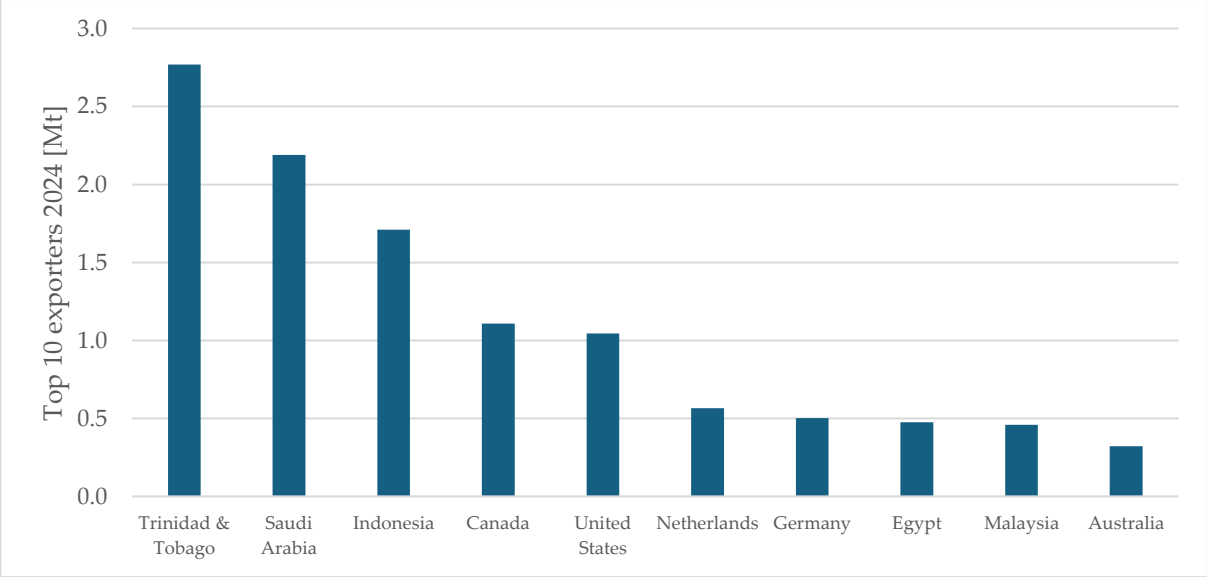

Figure 8 - Top 10 ammonia exporting countries in 2024 based on [12].

Figure 9 highlights India as the top importer with 2.4 Mt, followed by United States (2.2 Mt), Turkey and Belgium (0.8 Mt), followed by a group of countries clustering around 0.5 Mt, including China, despite being the world's largest producer.

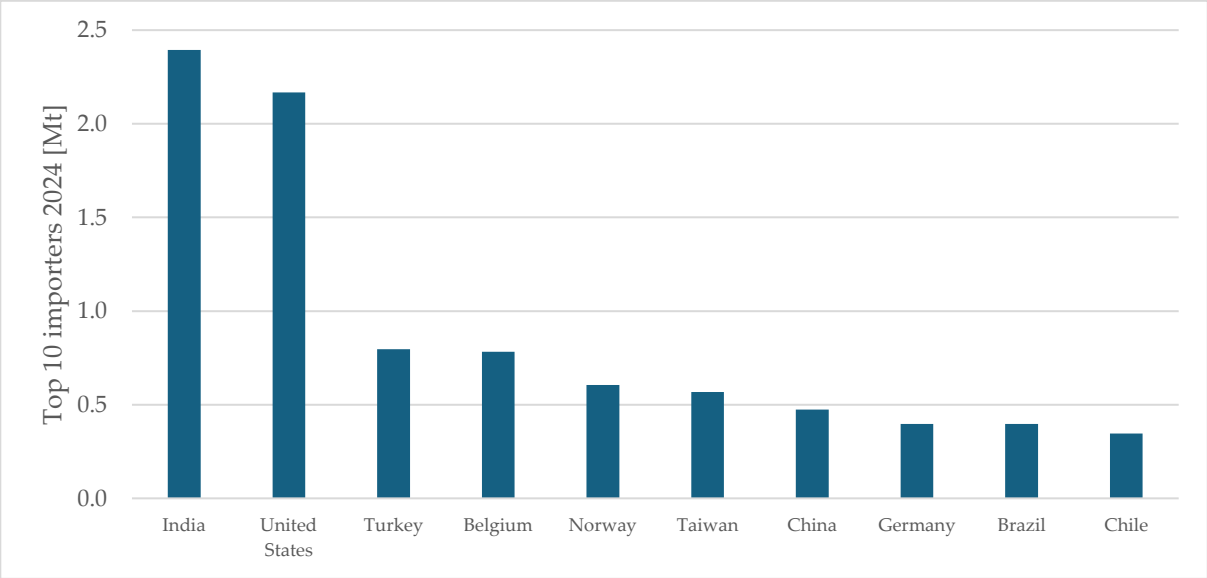

Figure 9 - Top 10 ammonia importing countries in 2024 based on [12].

Shifting from country rankings to regional balances, Figure 10 compares production with apparent consumption across major regions in 2019. Apparent consumption is defined as production plus net import/export, aligning production with cross-border flows to approximate the regional demand [6]. It highlights clearly that, despite China

is the largest producer, it is also a net importer, as well as other countries/regions such as India and United States. The only net exporters shown are Russia, Middle East, Indonesia and Latin America.

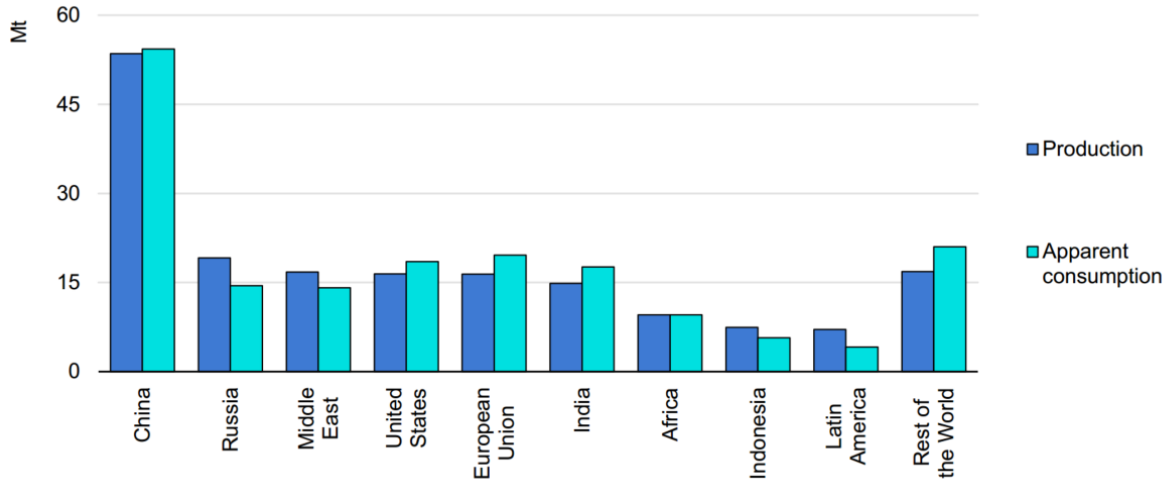

Figure 10 - Production and apparent consumption (production plus net import/export) of ammonia in 2019 by region [8].

Figure 11 visualises global ammonia trade flows and balances, in 2019 above the stated threshold of 0.1 Mt, providing a global network view and highlighting major origin-destination links and the distribution of balances across countries. The limited number of dominant links and nodes reinforces the idea that even if the amount of traded ammonia is relatively small compared to production, it can still be translated into concentrated international corridors.

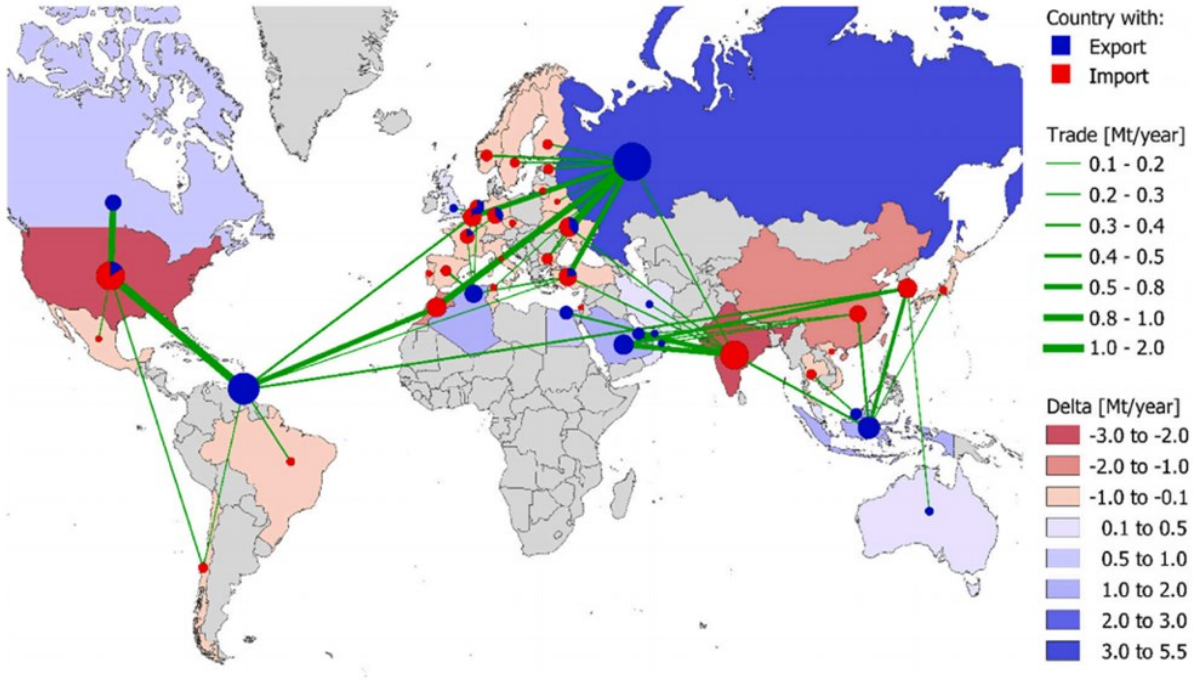

Figure 11 - Global ammonia trade flows and balances larger than 0.1 Mt per year in 2019 [13].

Ammonia market prices ranged between 100 USD/t and 600 USD/t from 2000 to 2020, while natural gas shortages starting in 2021 induced an increase above 1000 USD/t in all regions [9].

Published ammonia price assessments are based on information gathered from a wide range of market participants, including traders, producers, and buyers, with the aim of cross-checking transactions, firm bids, and offers wherever possible. Prices are assessed on a Free on Board (FOB) basis in the main export regions and on a Cost and Freight (CFR) basis in the main destination markets, aligning benchmark quotations with standard commercial terms. When sufficient liquidity exists, assessed ranges are anchored to confirmed deals that meet minimum volumes, strict delivery timescales, and defined specifications, while verification with both buyers and sellers is sought where possible. In markets that periodically lack liquidity, price ranges are assessed using judgement informed by market discussions, with a view to the range in which transactions could have taken place between a willing buyer and seller [14].

The following elements are used to describe physical ammonia pricing in published assessments:

- Market input: assessments are conducted by drawing on information from traders, producers, and buyers, with efforts to confirm deals and cross-check information across participants;

- Assessment logic: confirmed deals meeting minimum criteria are described as carrying the most weight, while judgement-based assessment is used when liquidity is insufficient;
- Quotation basis: pricing is assessed on FOB in export regions and CFR in destination markets;
- Contracting language: spot pricing and formula pricing are defined separately, distinguishing near-term cargo transactions from pre-agreed pricing calculations for future deliveries.

Within this reporting framework, spot pricing refers to specific cargoes scheduled to load within 40 days of agreement, while formula pricing is defined as an advance agreement for future delivery based on a predetermined calculation that may utilise published prices [14].

Table 2 summarises how these two contracting logics differ in practice and how they are represented in benchmark conventions.

Table 2 - Overview of spot and formula/contract-style pricing definitions and benchmark assessment labels for contract attributes.

	Spot (physical) pricing	Formula/contract-style pricing	Ref.
Definition	Specific cargoes scheduled to load within 40 days of agreement; cash prices net of credit.	Advance agreement for future delivery based on a predetermined calculation that may utilise published prices.	[14]
How it is labelled in benchmarks	Benchmarks are specified with spot/contract label plus basis, location, timing, and typical cargo size.	Some benchmarks are explicitly defined as contract-linked (CFR Tampa CP described as reflecting a monthly contract).	[15]

In the Platts fertilisers specifications, ammonia assessments are presented with explicit attributes, such as spot/contract label, basis (FOB or CFR), location definition, timing, and typical cargo size, and supporting consistent interpretation of benchmark quotations across regions.

For Europe, the CFR Northwest Europe assessment is specified on a CFR basis with an Antwerp/Rotterdam reference and is described as considering market activity at ammonia-importing terminals in Northwest Europe, defined as a Finland–France range.

The specifications also describe a CFR Tampa CP assessment as reflecting the monthly ammonia contract between Yara and Mosaic, illustrating how contract-linked benchmarks can coexist with spot assessments within published pricing frameworks

[15]. Overall, global ammonia production is geographically concentrated, while international trade remains a minority share of total output despite being organised through a limited number of dominant corridors [6]. Within this structure, benchmark assessments (FOB/CFR) and contracting conventions (spot vs. formula) provide a consistent basis to interpret regional price signals and compare reported market information across locations and time [14], [15].

Recent benchmark prices are reported for Northwest Europe for September, October and November 2025, with a distinction on how ammonia is produced, based on emissions profiles: grey ammonia is produced from fossil feedstocks without CO_2 capture, blue includes Carbon Capture and Storage (CCS), and green ammonia is produced using renewable electricity coupled with water electrolysis (See Section 2.1).

These prices differ across colours because they reflect different production pathways and associated cost structures, and they may also include different delivery assumptions. Accordingly, Figure 12 reports separate benchmark prices for each colour/pathway rather than a single, uniform price. The figure shows that grey and blue ammonia prices in Northwest Europe go up from September to November 2025, suggesting that the "standard" ammonia market has less supply available over the period, increasing also the blue benchmark. By contrast, green ammonia prices stay almost flat. The three green lines represent deliveries from three different origins (Eastern Canada, US Gulf Coast and Middle East) and they remain very close to each other, suggesting a stable price level in these months [16].

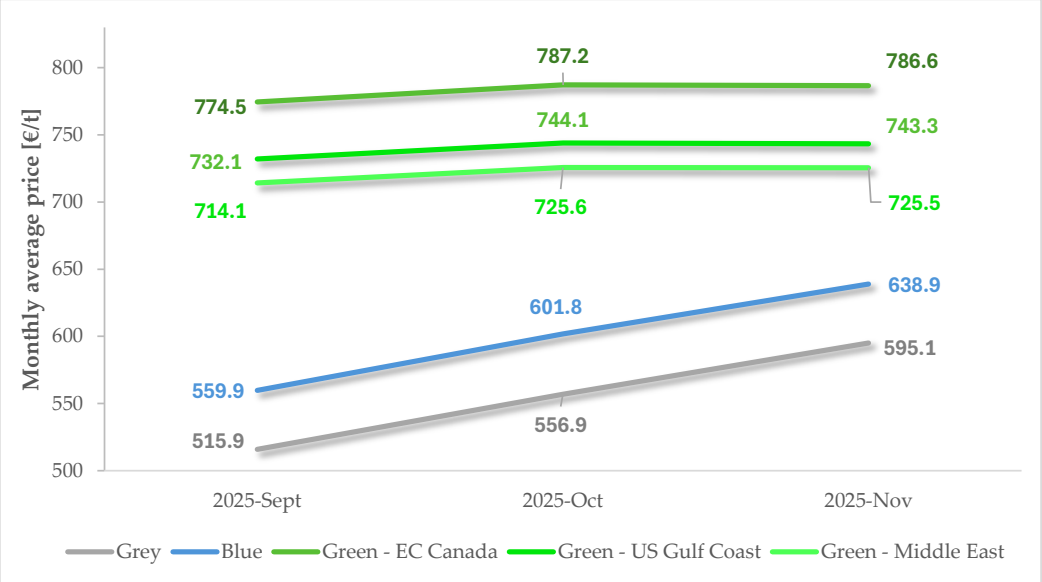

Figure 12 - Northwest Europe ammonia benchmark prices [17] (*).

(*) Monthly averages of daily assessments; values converted from USD to € dividing by the monthly average exchange rate (USD/€) from the Banque de France/ECB series [18].

1.4. Current uses of ammonia

Ammonia's most important role within society is through agriculture, since it is the starting point for all mineral nitrogen fertilisers and therefore links nitrogen in the air with food production. The historical link between fertiliser use, crop yields, and population growth is discussed in Section 1.2 [6], [8].

Therefore, in current markets, demand is driven substantially by fertilisers (roughly 85%), while the remainder is associated with a broad set of industrial applications (Figure 13) [8].

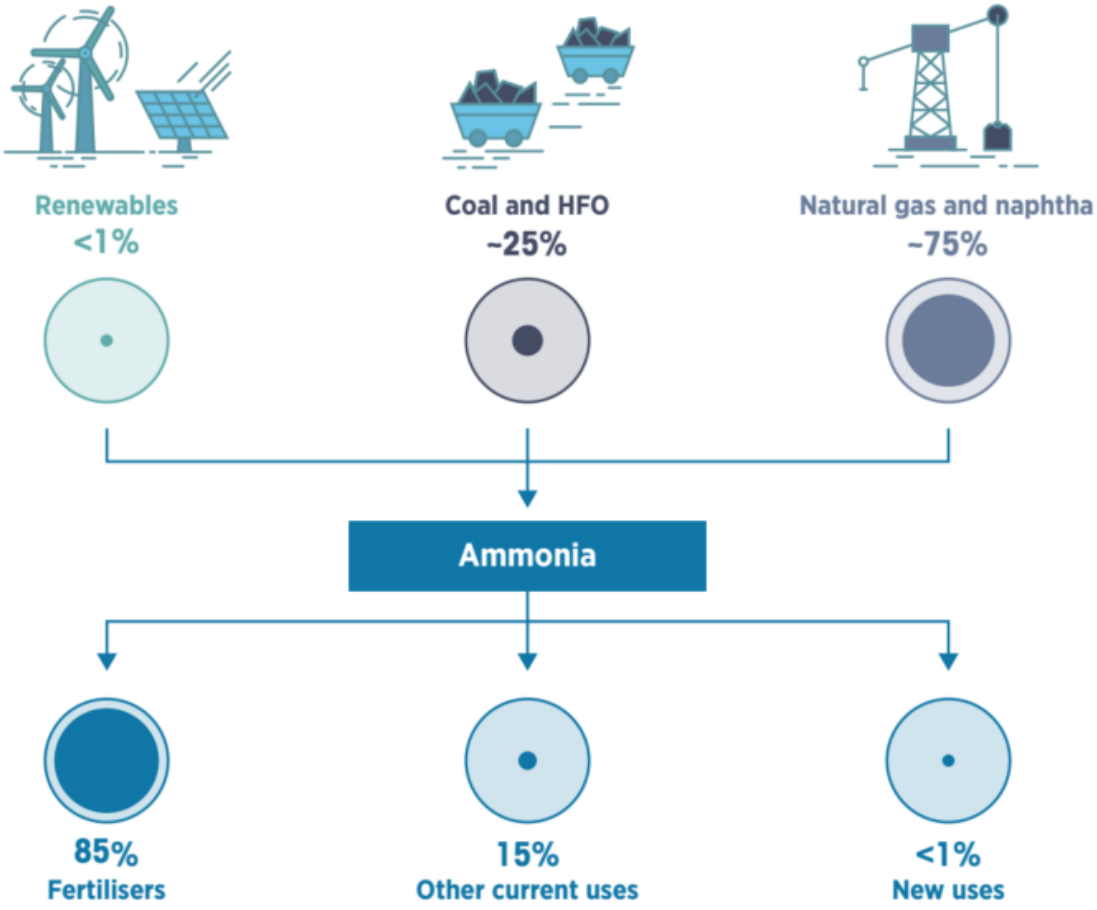

Figure 13 - Share of ammonia production and uses [9].

Ammonia is applied directly to land only in a minority of cases (notably in China, Figure 14); elsewhere it is most commonly converted into downstream fertilisers, such as urea, ammonium nitrate and ammonium phosphate (MAP/DAP) and ammonium sulphate (Figure 15 and Figure 16). These products are generally more convenient for storage, transport and field application than anhydrous ammonia. However, their

manufacture also require additional feedstocks such as CO_2 (for urea), nitric acid/oxygen (for ammonium nitrate) and phosphoric or sulphuric acid (for MAP/DAP and ammonium sulphate) [8].

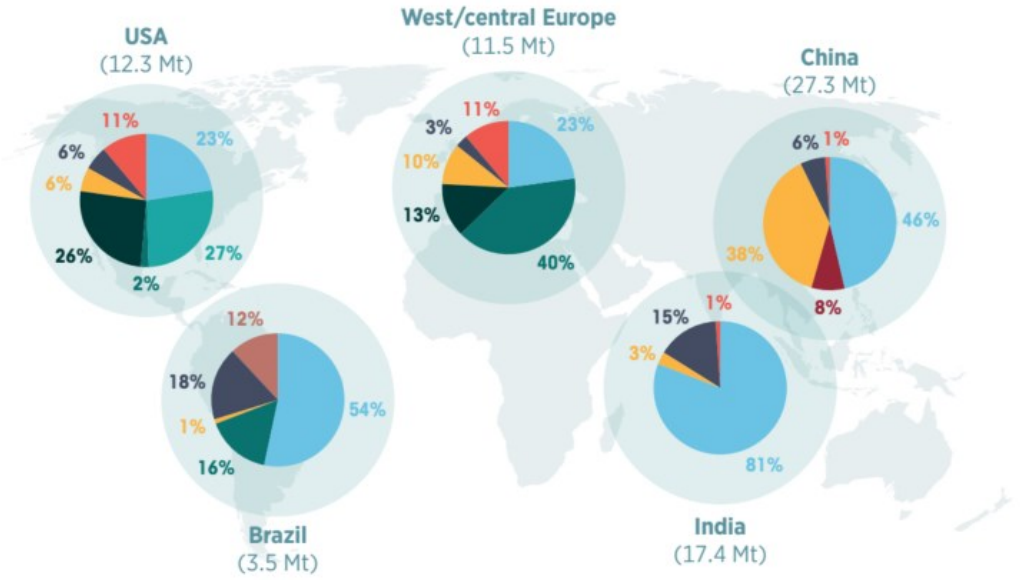

Figure 14 - Share of nitrogen fertiliser application by region in 2019 [9].

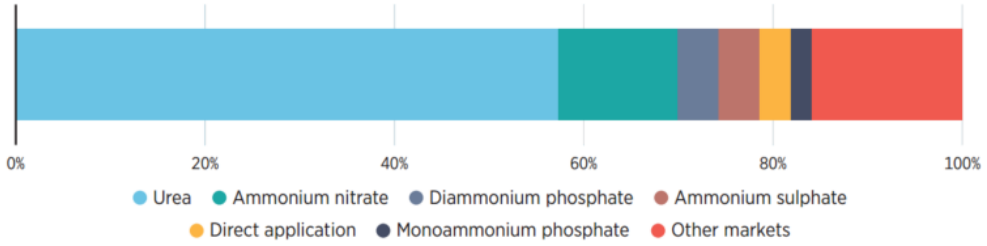

Figure 15 - Global demand share in 2019 by end-use product [9].

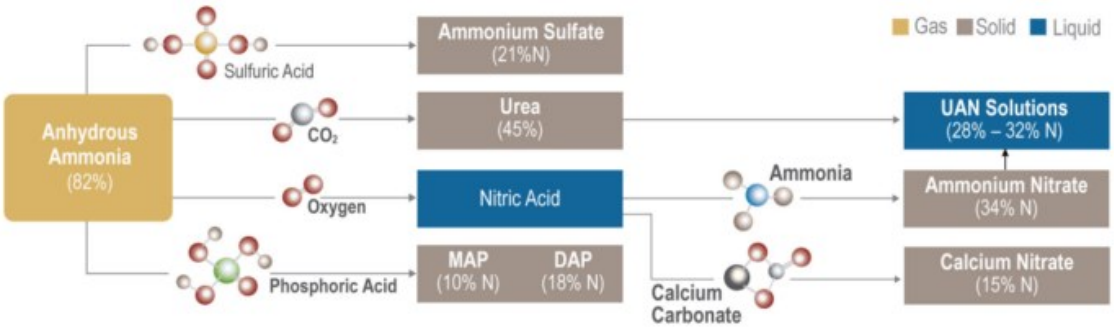

Figure 16 - Main conversion routes from anhydrous ammonia to nitrogen fertiliser products (urea, nitric acid, ammonium nitrate, MAP/DAP, ammonium sulphate, UAN, calcium nitrate) [6].

Within these conversion pathways, urea is framed as the most common derivative, accounting for around 55% of the demand, with most of that urea used directly as fertiliser, while a smaller share is used to produce urea ammonium nitrate and the remainder supports industrial applications [8].

Urea is also industrially used as an intermediate in durable resins such as urea formaldehyde and as a chemical agent to reduce nitrogen oxides (NO_x) emissions from power plants and diesel engines. Another important conversion route is nitric acid production, which is then used to make different grades of ammonium nitrate either serving as a fertiliser or industrial explosives for mining, quarrying, and tunnelling, illustrating how ammonia-derivatives can support both agriculture and industrial activity (Figure 17).

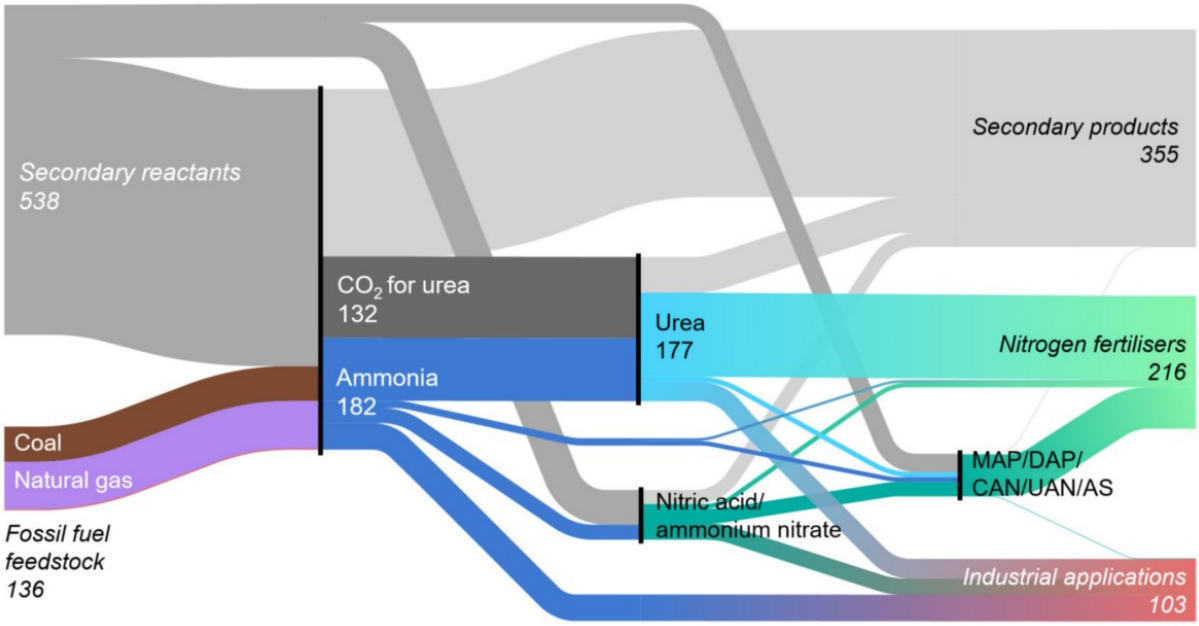

Figure 17 - Sankey diagram of ammonia supply chain in mass flows [8].

Ammonia is described as a fundamental intermediate for producing other chemicals and is the second most produced worldwide by mass after sulphuric acid, with non-fertiliser demand spanning multiple industrial sectors such as plastics, explosives and synthetic fibres [8], [9].

Within these non-fertiliser uses, ammonia is reported to support industrial supply-chains (including via acrylonitrile for durable products such as plastics, rubber and fibres) and to serve direct applications such as air-pollution control, refrigeration and cleaning, alongside other industrial uses including textiles, pharmaceuticals and dyes [8].

This established role in both agricultural and industrial markets is supported by the fact that ammonia has been handled in large quantities for many decades, translating into mature storage systems, transport, and distribution networks and associated codes, standards, and regulations, which are specified in the infrastructure chapter (Section 0) [9].

1.5. Environmental implications and health hazards

Ammonia is characterised by a lethal concentration far below flammability thresholds, so toxicity dominates the safety risk profile. This section highlights the main environmental and human-health concerns linked to ammonia across its life cycle, focusing on fossil-based production, fertiliser-related emissions within the nitrogen cycle, and the consequences of direct releases [3].

Current ammonia production (fossil-based) is highly energy intensive and requires about 8.6 EJ per year, which correspond to roughly 2% of global final energy consumption [6]. This process emits around 0.5 Gt_{CO_2} per year (roughly 1% of global CO_2 emissions), accounting for 15-20% of the entire chemical sector; therefore, it is framed as a major climate-relevant activity within this industry [9].

Fertiliser-related emissions are quantified at about 434 Mt_{CO_2}/y, including 315 Mt_{CO_2}/y from direct production emissions and 119 Mt_{CO_2}/y from external power/steam consumption for fertiliser synthesis [6].

Downstream impacts are largely governed by the nitrogen cycle, defined as the set of pathways through which reactive nitrogen introduced by fertilisers circulates and transforms between the atmosphere, soils, vegetation and water bodies (Figure 18) [6].

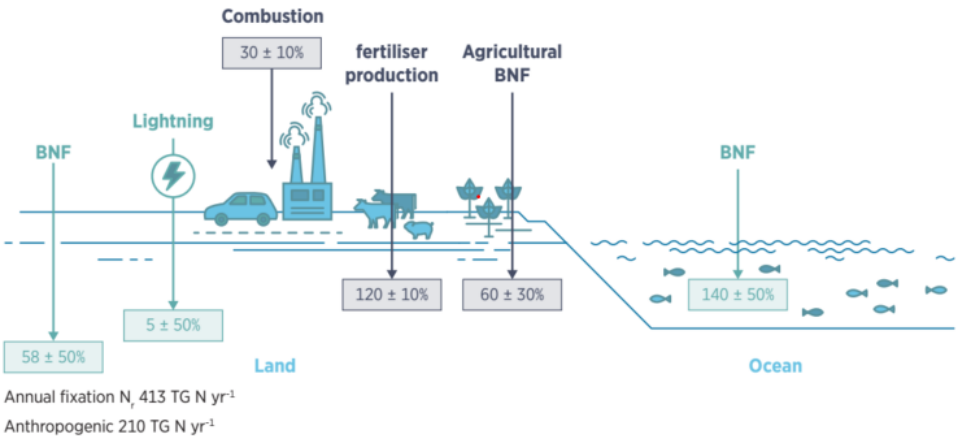

Figure 18 - Global nitrogen fixation flows in 2010 (natural and anthropogenic processes) [9].

Ammonia is relevant to this cycle because agricultural activities (including livestock and fertiliser volatilisation) are estimated to contribute more than 80-90% of global ammonia emissions, which can be removed from air through dry and wet deposition, becoming an additional nitrogen input to land and aquatic ecosystems [6].

Field-stage emissions are also relevant because nitrous oxide (N_2O) is released during application of ammonia-derived fertilisers, regardless of how ammonia is produced, while different fertiliser types show substantially different post-application N_2O emission levels [6].

Urea is highlighted as a specific case because it is produced by combining ammonia with CO_2 (about 0.75 t CO_2 per tonne of urea as feedstock), which is released to the atmosphere when applied as a fertiliser [9].

Beyond greenhouse gases, direct ammonia release in the air is described as a precursor for secondary inorganic aerosols, because it can react with acidic species to form ammonium salts, contributing to fine particulate matter formation (PM2.5), thereby degrading air quality (Figure 19) [6], [7].

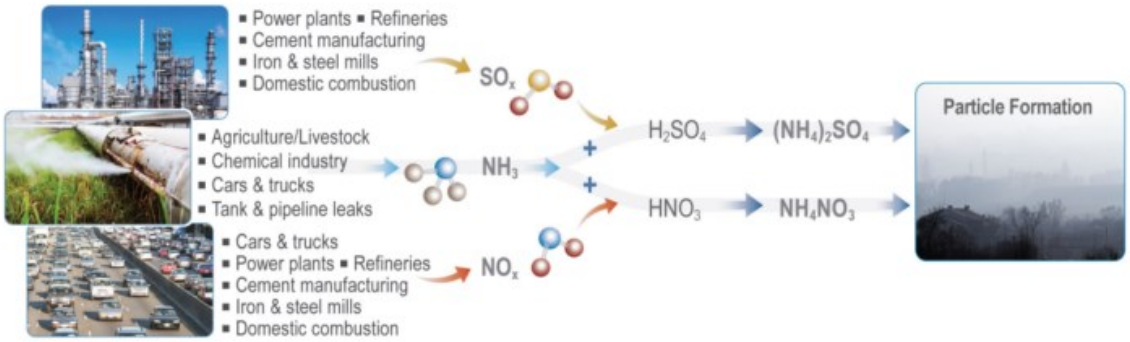

Figure 19 - Examples of secondary particle formation pathways involving ammonia [6].

Direct releases to water are associated with local ecological hazards, since ammonia is highly toxic to aquatic organisms, and nitrogen inputs contribute to eutrophication, triggering harmful algal blooms, oxygen depletion, and fish kills [6].

Human health hazards depend directly on ammonia toxicity, with lethality reported around 0.5% in air. Acute Exposure Guideline Levels (AEGL) for ammonia are reported by the United States Environmental Protection Agency (EPA) as concentration thresholds that depend on exposure duration, and they are used to interpret short-term public exposure risks during accidental releases (Table 3) [2].

Table 3 - EPA AEGL concentration for ammonia in ppm [2].

AEGL category	10 min	30 min	60 min	4 h	8 h
AEGL-1	30	30	30	30	30
AEGL-2	220	220	160	110	110
AEGL-3	2700	1600	1100	550	390

These categories correspond to:

- AEGL-1: notable discomfort or irritation but temporary and non-disabling;
- AEGL-2: may cause serious or irreversible effects and may impair an individual's ability to escape;
- AEGL-3: can lead to life-threatening effects or death [2].

Overall, ammonia presents a dual impact profile: upstream climate burdens remain high when production relies on fossil fuels, while downstream use and accidental releases can drive air-quality degradation, eutrophication, and acute human-health risks. Reducing these impacts requires both low-carbon production routes and strict control of emissions and leak prevention across storage, transport, and end uses.

1.6. Strategic importance in the energy transition

Ammonia is set to become strategically important in the energy transition, but additional emissions reductions depend on decarbonising its production, especially when used as an energy-vector and a hydrogen-carrier [19]. This section summarises four connected elements in a single narrative: the production's decarbonisation imperative, ammonia's role as an energy vector, its function as a hydrogen carrier and traded derivative, and the scale of demand and market growth implied by relevant transition scenarios [19], [20], [21]. Figure 20 illustrates how renewable or low-emission ammonia is integrated in the economy along the whole supply chain, highlighting also new uses as an energy- and hydrogen-vector.

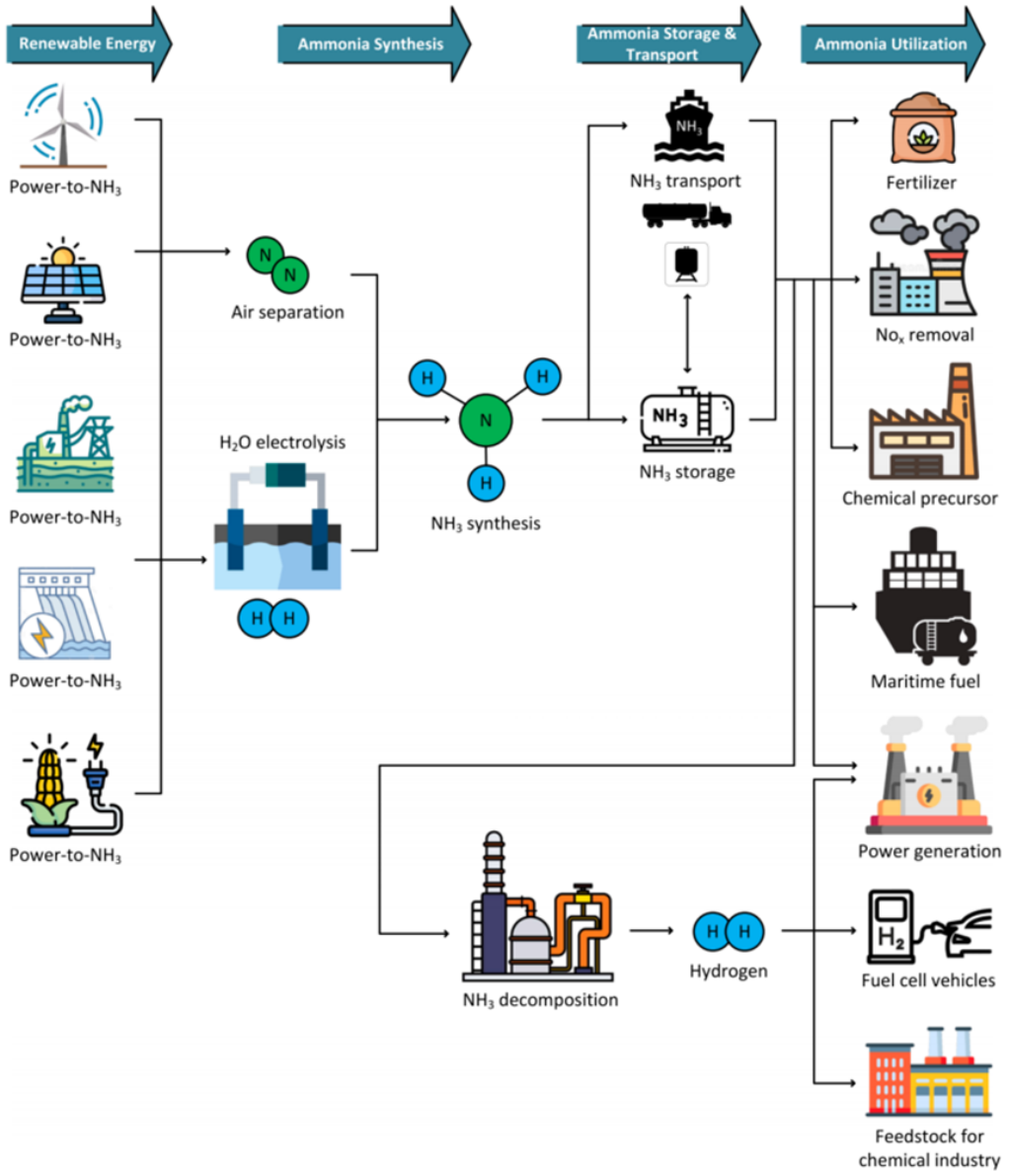

Figure 20 - Layout of renewable ammonia economy [7].

Decarbonising ammonia production becomes a prerequisite for any additional climate benefit because low-emissions hydrogen remains marginal in current supply and grows from a very low base in the early 2020s (Figure 21).

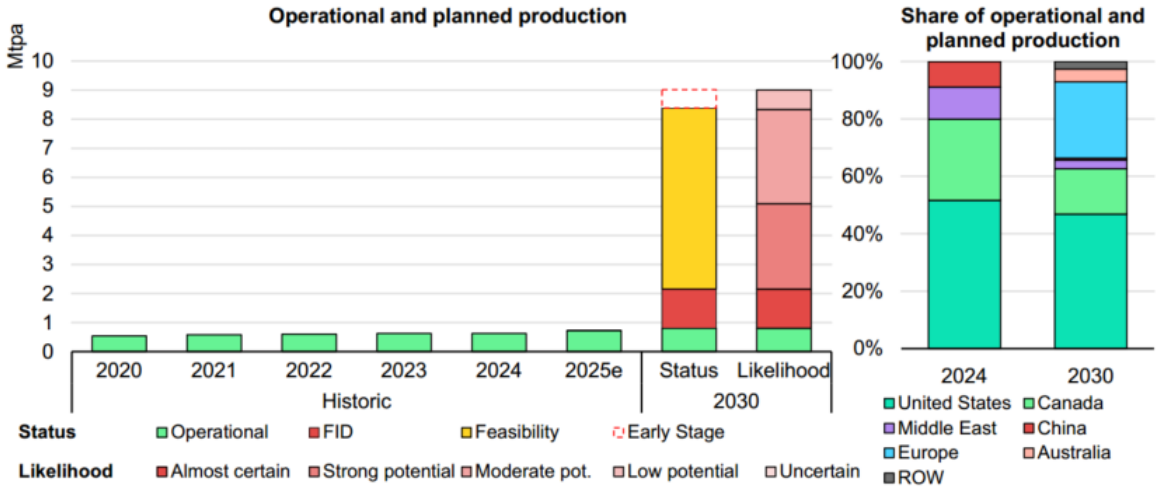

Figure 21 - Production of low-emission hydrogen from fossil fuels with carbon capture, utilisation and storage, historical and from announced projects, 2020-2030 [20].

Hydrogen production is still largely fossil-based and is associated with about 980 Mt of CO_2 emissions, while around 100 Mt of hydrogen are used in the energy sector in 2024, with roughly 55% consumed in the industrial sector, mainly for ammonia and methanol, and the remainder used in refineries [19].

Scaling low-emission hydrogen depends on announced projects advancing through investment and construction stages, which positions low-emission ammonia as dependent on upstream deployment dynamics [20].

Figure 22 shows that demand for low-emissions hydrogen and hydrogen-based fuels increases over time while unabated demand declines, and it indicates that ammonia becomes a material component of hydrogen-based fuel use, particularly in shipping.

Ammonia functions as an energy vector because it can be produced with low emissions, stored and transported more easily, and then used directly as a fuel in applications where direct electrification remains difficult. In the Net Zero Emissions (NZE) Scenario, low-emissions ammonia, synthetic methanol and hydrogen together meet around 30% of shipping energy needs by 2035 [19].

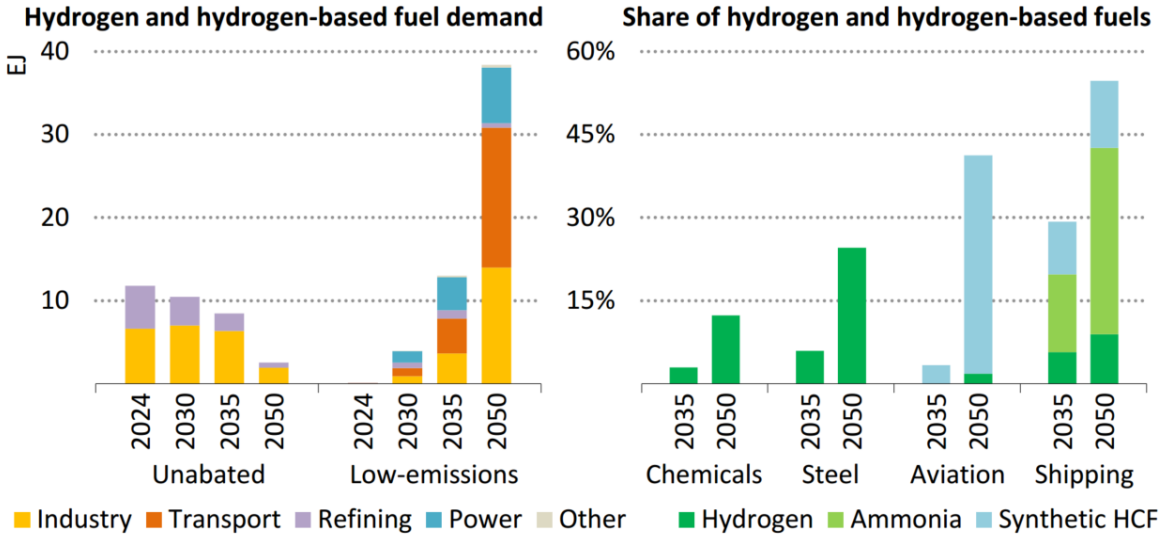

Figure 22 - Hydrogen demand by sector, and hydrogen fuel use in selected sub-sectors in 2035 and 2050, according to NZE Scenario [19].

Low-emissions hydrogen and ammonia also support power-system flexibility, because they are described as fuels that can contribute to emissions reductions from existing plants and provide flexibility where needed. In the NZE Scenario, low-emissions hydrogen and ammonia together supply around 1.5% of total fuel needs in the global power sector by 2035, linking ammonia to dispatchable generation and system balancing [19].

The decarbonisation of shipping sector also highlights ammonia's relevance, because emissions reductions in the Announced Pledges Scenario (APS) rely heavily on switching to low-emissions fuels alongside efficiency improvements. Figure 23 suggests that the mitigation pathway is led by low-emissions fuel switching and that ammonia is highlighted as the main contributor in the long-term reductions profile.

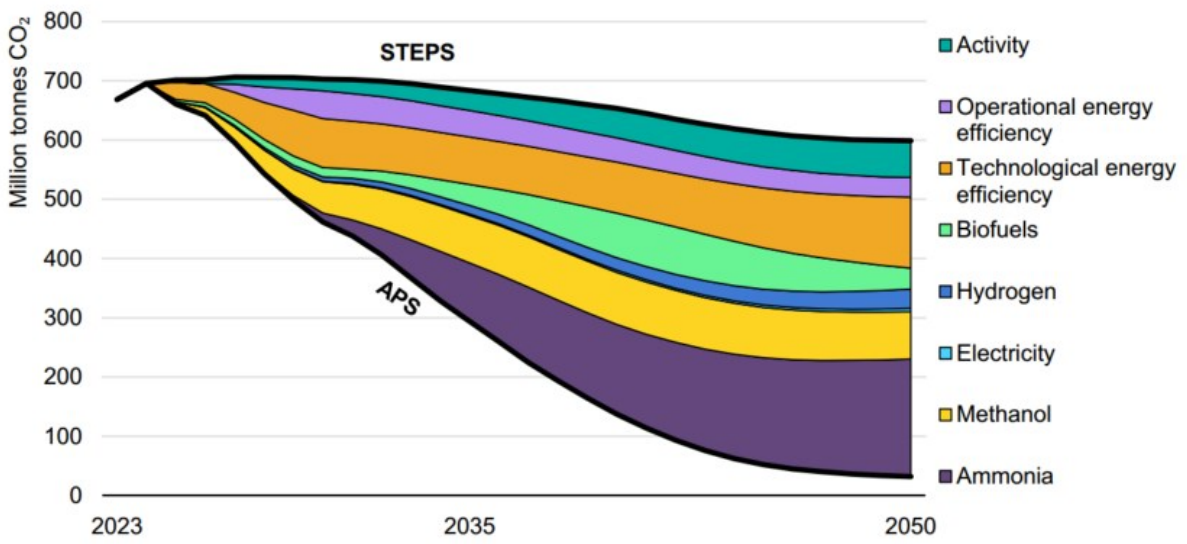

Figure 23 - Global energy-related CO_2 emissions in international shipping by scenario and reductions in the Announced Pledges Scenario (APS) relative to the Stated Policies Scenario (STEPS) by mitigation measure [21].

Ammonia's role as a hydrogen carrier can also be crucial, because it enables transport, storage and trade through forms that already have an established handling and shipping practices. International trade in hydrogen itself remains limited because most of it is produced and consumed on-site, while ammonia is already traded, with around 10% of global anhydrous ammonia production transported as liquefied gas in tankers. Global anhydrous ammonia trade amounts to around 20 Mt/y, which corresponds to about 3.5 Mt/y in hydrogen equivalent [20].

Figure 24 connects ammonia's carrier role to the fact that ports already handle it in many countries and shows that new facilities are planned across additional countries, which supports an expansion of traded hydrogen-based derivatives.

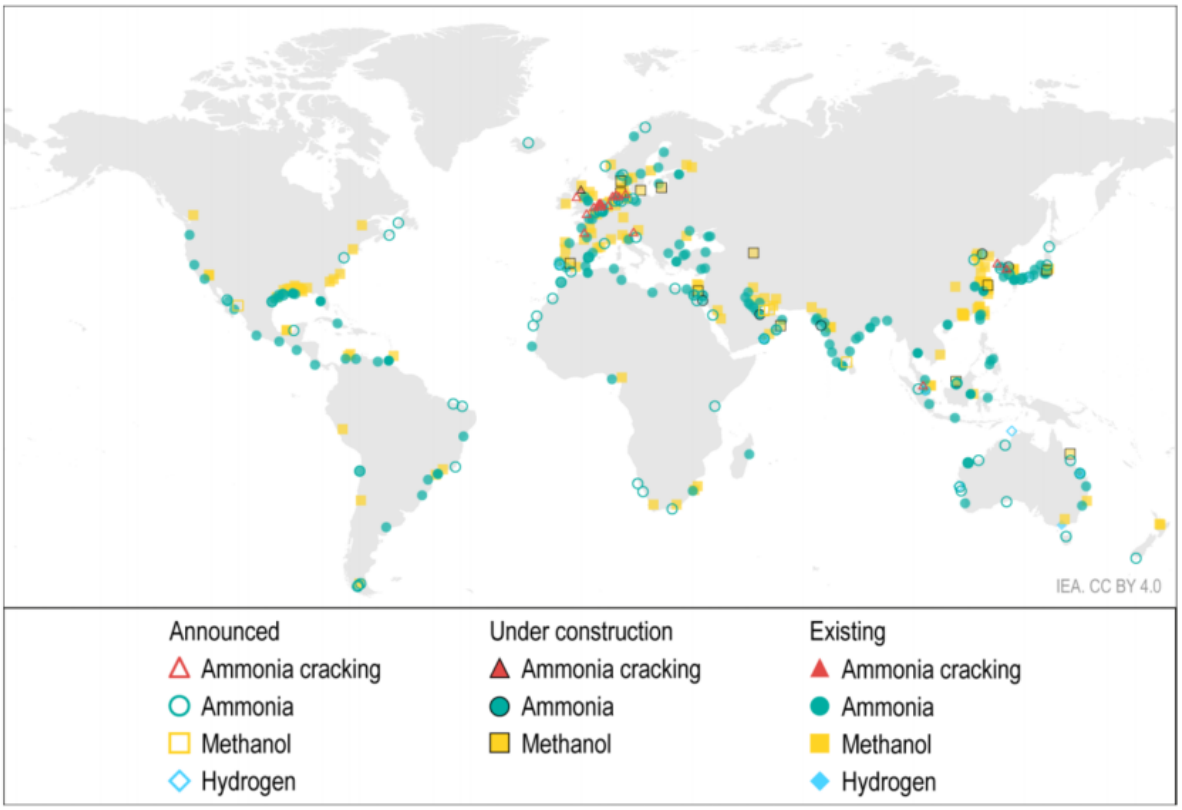

Figure 24 - Existing and announced port infrastructure projects
for hydrogen and hydrogen-based fuels trade and bunkering [20].

These new applications translate into substantial market expansion in transition scenarios: ammonia demand almost triples by 2050 in both the APS and the NZE Scenario, driven by the emergence of new applications including use as a shipping fuel and in power generation. Energy applications grow from virtually nothing today to around 300 Mt by 2050 in both scenarios, indicating that energy-transition uses become a major driver of total ammonia demand growth (Figure 25).

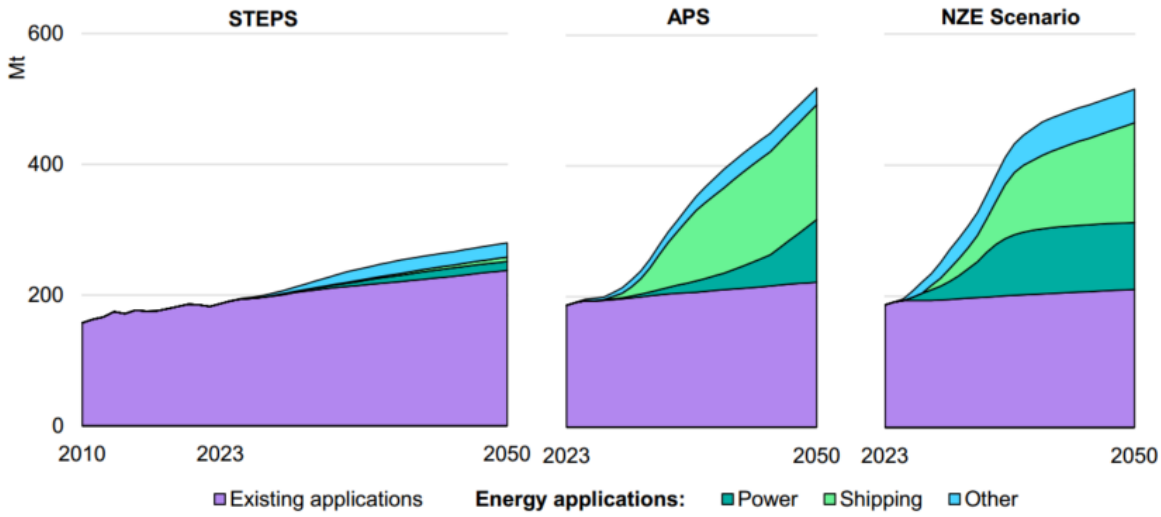

Figure 25 - Global demand of ammonia by application and scenario, 2010-2050 [21].

In conclusion, ammonia becomes strategically important because it connects near-term industrial decarbonisation needs with quantified transition roles in shipping and power, while also enabling international movement of hydrogen-derived energy through an already established traded derivative [19], [21].

2 Ammonia production methods

This chapter provides an overview of ammonia production methods, starting from the conventional Haber-Bosch synthesis loop, introducing the main upstream routes for hydrogen and nitrogen supply, and then moves to novel/emerging production routes that either rely on the Haber-Bosch process, but with milder conditions, or bypass the conventional synthesis loop completely.

2.1 Haber-Bosch based systems

Industrial ammonia synthesis is accomplished by reacting hydrogen and nitrogen according to the equilibrium reaction presented in Equation (1) (Section 1.2); due to its exothermic nature, heat recovery is an inherent design feature in the synthesis loop [6]. The reaction is carried out at high temperatures and pressures (typically 350-500°C and 100-400 bar) over an iron-based catalyst to reach industrially relevant production rates, while maintaining a favourable equilibrium towards ammonia [9]. However, only a limited fraction of reactants is converted in a single pass through the reactor, because of the trade-off between kinetics and equilibrium. Modern plants commonly achieve about 10-15% conversion rates per pass (up to 20% for very recent plants); therefore, the reactor's outlet stream is cooled so that ammonia is liquified and removed, while the remaining gas is recycled back until virtually all (>98%) the hydrogen and most the nitrogen (around 95%) are converted, leading to overall conversion rates that approach 100% (Figure 26) [6], [8].

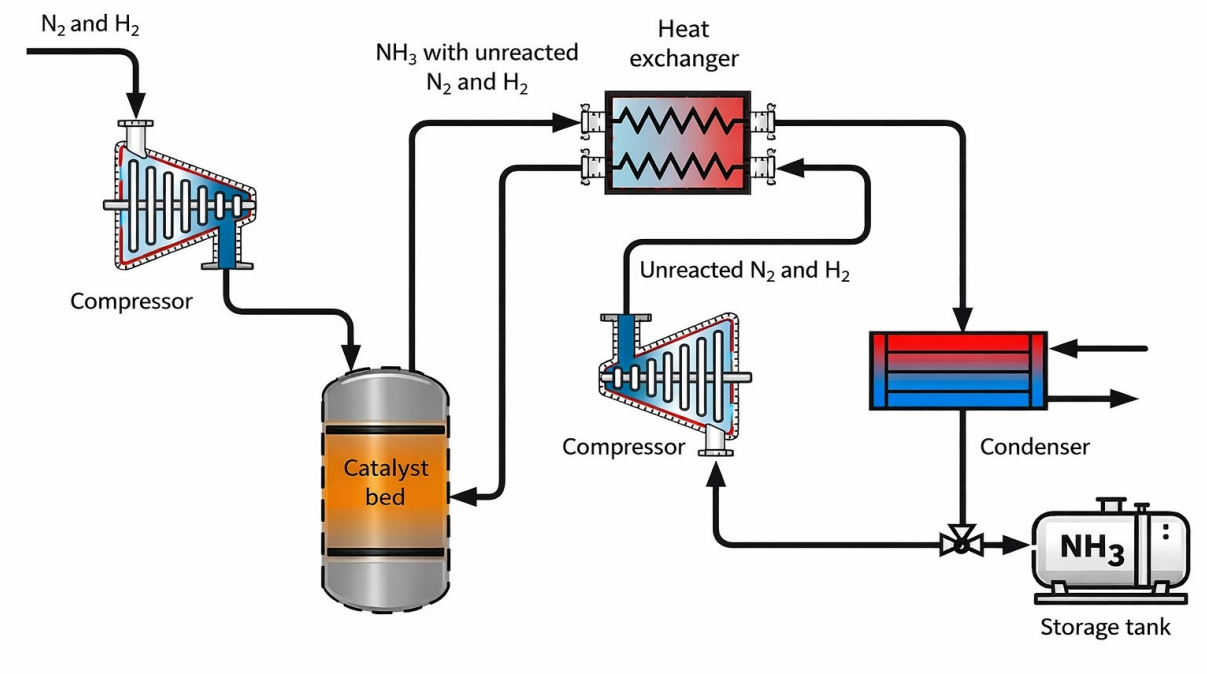

Figure 26 - Simplified layout of Haber-Bosch ammonia synthesis loop [7].

Therefore, the synthesis loop comprises a high-pressure catalytic reactor, followed by heat recovery and cooling to liquefy ammonia. The reactor effluent is first cooled in a heat exchanger to recover heat (which is not depicted in the figure and is typically used to generate stream), then further cooled in a condenser to form liquid NH_3. The condensed ammonia is removed in a separator and sent to storage, while the remaining gas is returned to the reactor inlet via a recycle compressor/circulator. A small purge is taken from the circulating gas to prevent the build-up of inert species (argon and methane) in the loop. Fresh make-up gas is compressed and mixed with the recycled stream to reach the target operating pressure and maintain the desired inlet composition. [6].

Nitrogen is obtained from air and delivered to the synthesis loop as purified N_2. Large-scale production plants commonly adopt a cryogenic Air Separation Unit (ASU), in which air is compressed, purified and distilled at low temperature to produce a high-purity stream. This solution is well established and matches the large, steady nitrogen flowrates required by conventional Haber-Bosch operation; however, it is not well suited for intermittent operation below 50% of the load [9]. For smaller-scale and more flexible configurations, nitrogen can alternatively be produced using Pressure Swing Adsorption (PSA), in which air is passed through an adsorbent bed that preferentially retains oxygen and other components, releasing a nitrogen rich product. PSA typically offers simpler, modular equipment, faster start-up/shut-down and better load-following behaviour, which can make it suitable for modular and intermittent

"power-to-ammonia" systems; in contrast, the ASU is preferred when very large flowrates and high purity nitrogen are required by large-scale plants operating close to steady state [9], [22].

Hydrogen can be produced from multiple feedstocks and by multiple process families. Many organisations colloquially use a colour-based taxonomy for its production that can be applied also to ammonia; however, the naming convention is not universally recognised and can lead to misconception/misperception [23]. This thesis work applies the colour labels shown in Table 4 along with the Technology Readiness Level (TRL) associated with each production pathway.

Table 4 - Hydrogen production pathways: associated "colour" classification and TRL. Author elaboration based on [24].

Hydrogen production	Colour	TRL
Coal gasification without CCS		9
SMR/ATR/Partial Oxidation without CCS		9
Coal gasification/SMR/ATR/Partial Oxidation with CCS		6-8
Natural gas Cracking/Pyrolisys/Chemical Looping Cracking		3-5
Nuclear powered Electrolysis		7-9 (*)
Renewable powered Electrolysis		7-9 (*)
Biomass gasification (with CCS)		5-6 (3-5)
Grid powered Electrolysis		7-9 (*)

(*) Range reflects the distinction between electrolyser module maturity and the maturity of the fully integrated ammonia production chain at scale [8].

Brown (coal-based) ammonia production generates hydrogen by converting coal into a syngas via gasification with oxygen and steam [8]. The gasifier produces raw syngas containing H_2, CO, CO_2, CH_4 and other hydrocarbons, as well as contaminants such as sulphur species, particulates and trace metals, that must be removed before downstream catalytic steps. Consequently, the process includes a syngas clean-up section to remove impurities, avoiding catalyst poisoning and aligning with air-pollutant emission requirements [8]. The syngas is then conditioned in a Water-Gas Shift (WGS) unit, where CO reacts with steam to form additional H_2 and CO_2 [8]. Coal-based schemes are commonly described as using a Sour Gas Shift (SGS) unit with a cobalt-molybdenum (CoMo) catalyst that is designed to operate in a sulphur-containing environment [25]. Then, the shifted gas is passed through an Acid Gas Removal (AGR) unit to remove CO_2 and sulphur species before reaching the

ammonia synthesis loop; a representative configuration reports CO being reduced below 1% in volume and then treated in a chilled methanol wash (such as Rectisol) to remove CO_2 and sulphur compounds [8], [25]. When the CCS unit is not applied, the separated CO_2 stream is either vented or routed to a urea production plant, while the sulphur stream is routed to a recovery unit. Downstream, additional purification is applied to remove residual CO and CH_4 before the syngas enters the Haber-Bosch synthesis loop [25].

Grey (natural gas-based) ammonia production relies on hydrogen produced by reforming natural gas into syngas and conditioning it to obtain a purified H_2 stream, or a mixture of H_2 and N_2, suitable for the Haber-Bosch synthesis loop. The first step consists in desulphurisation to remove sulphur compounds from the natural gas feed, since they would poison downstream reforming and shift catalysts. In the most widespread configuration, Steam Methane Reforming (SMR) converts methane and steam to a CO and H_2 rich syngas, while requiring external firing, since the main reforming reaction is endothermic [8]. A representative plant scheme therefore includes a fired primary reformer followed by a secondary reformer (WGS) for CO conversion, CO_2 removal, and compression before reaching the ammonia synthesis loop [25]. Alternative grey routes rely on oxygen-based oxidation to supply process heat outside the reactor. Autothermal Reforming (ATR) reacts hydrocarbons together with steam and pure oxygen, to produce syngas containing H_2, CO and CO_2, with SMR and partial oxidation occurring simultaneously in the reformer. Partial Oxidation (POX) supplies heat through the exothermic internal combustion of part of the methane with oxygen, generating at the same time H_2 and CO in the process [8]. Regardless of the front-end choice, CO is converted into CO_2 through WGS reaction, and then is removed from the mixture before the hydrogen-containing syngas is routed onward [9]. Before entering the synthesis loop, residual CO_x must be limited to protect the Haber-Bosch catalyst; thus, the final purification step is typically methanation, where CO_x react with H_2 to form CH_4 [8]. Typically, in SMR-based plants, nitrogen can also be supplied without a dedicated unit by introducing air directly in the secondary reformer, so that it is supplied into the process gas while oxygen is consumed in the reforming/oxidation reactions [25].

Blue ammonia routes retain the same core hydrogen production pathways as the brown and grey counterparts but add CO_2 capture and route this stream to conditioning, compression, transport and permanent geological storage rather than releasing it straight to the environment or using it on-site. In conventional reforming, a concentrated process CO_2 stream is already separated from the syngas using chemical or physical absorption technologies, and capture from this stream is described as mature, enabling CCS to focus therefore on preparing the carbon dioxide

for downstream processes and ensuring it reaches a storage site [8]. Many ammonia production plants already recover CO_2 for urea production, but permanent storage needs additional steps such as compression and transport to a permanent storage location [8]. For SMR-based systems, CO_2 is generated from two main streams: a concentrated process CO_2 stream produced during H_2 production and a dilute stream from reforming firing [9]. In ATR plants, a higher proportion of total CO_2 is concentrated, while a lower proportion is present in flue-gases, which makes the overall carbon dioxide stream more compliant with CCS than SMR arrangements [8]. In coal-gasification routes, CO_2 is separated during AGR, and in the absence of storage, the CO_2 overhead stream is vented or routed to urea production plants [25]. When the CCS is applied, the separated carbon dioxide stream becomes the input of the CCS chain for conditioning and storage, while the purified syngas proceeds to the synthesis loop [8].

Turquoise ammonia routes supply hydrogen without forming CO_2, most commonly by splitting natural gas into hydrogen and solid carbon. This process is referred to as methane pyrolysis or cracking and involves very high-temperature heat to split methane into its constituents by using three main technologies or different variations of these: plasma, thermal and catalytic. The produced hydrogen is then routed as feedstock to the same Haber-Bosch synthesis loop used in conventional configurations (Figure 27) [9].

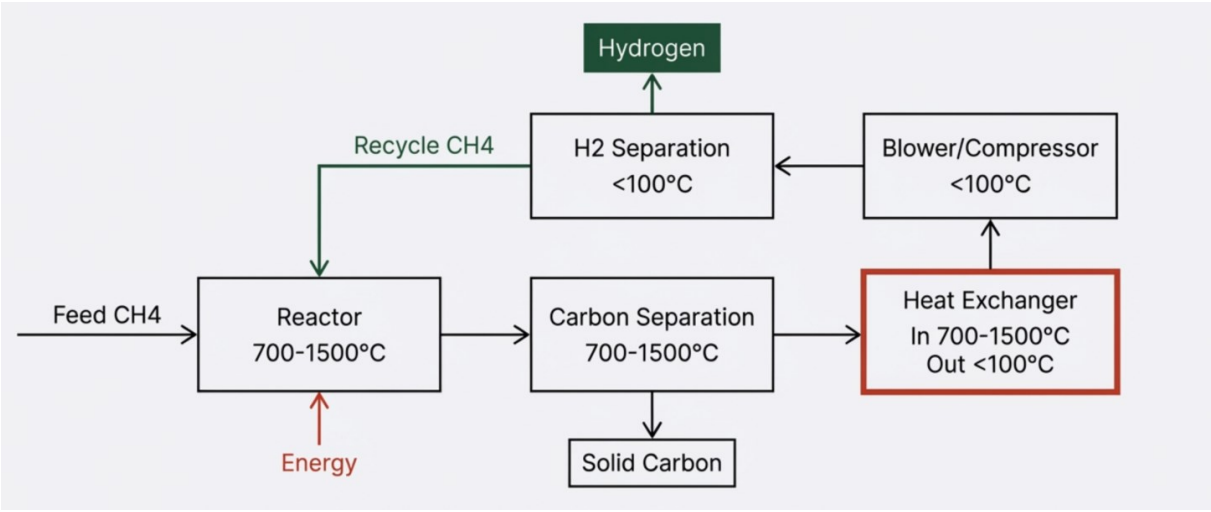

Figure 27 - Generic process flow diagram of methane pyrolysis/cracking. Modified from [26].

Another process-variant, still labelled as turquoise, is chemical looping methane cracking (CLMC). The process supplies hydrogen via a cyclic operation in which CH_4 is converted to H_2 while carbon is retained in solid form on a circulating solid material,

and a separate regeneration step removes the accumulated carbon using a CO_2-containing stream. A simplified schematic of the CLMC process and the corresponding reactions are provided in Figure 28.

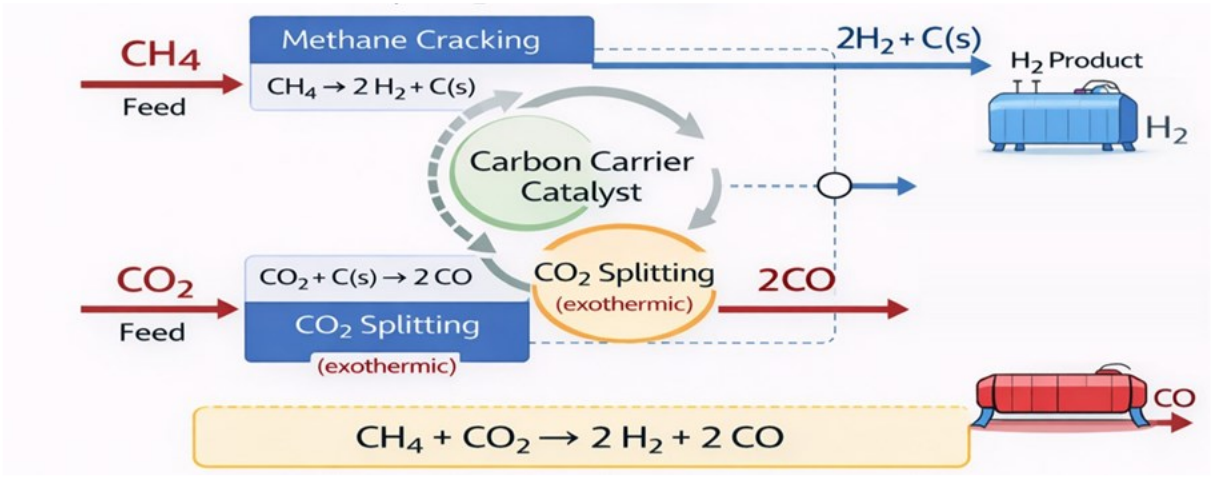

Figure 28 - Schematic of CLMC: CH_4 is cracked to H_2 and solid carbon, which is subsequently gasified by CO_2 to produce CO. Author elaboration based on [27].

Pink ammonia routes produce hydrogen from water electrolysis powered by nuclear energy. Before routing the electrolyser outlet to the synthesis loop, some conditioning steps are typically applied: oxygen and water are removed, and the hydrogen is compressed to the pressure required by the synthesis section (Figure 29).

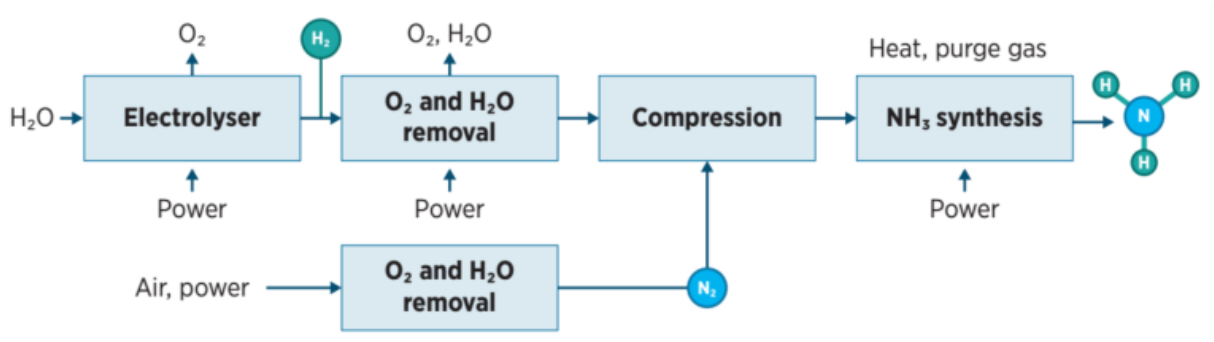

Figure 29 - Overview of steps involved in hydrogen conditioning for electrolysis-based routes [9].

In addition to Low-Temperature Electrolysis (LTE), the literature highlights also the High-Temperature (HTE) option, which can reduce the electricity consumption by supplying part of the required energy as heat/steam; therefore, nuclear plants are discussed as potential sources of both electricity and steam/process heat for this unit

[9], [28]. Beyond electrolysis, thermochemical water splitting cycles (Cu-Cl cycles) are also presented as an option for nuclear-based hydrogen production [9].

Green ammonia is produced when renewable electricity supplies the electrolyser to generate hydrogen [9]. Since direct coupling to variable renewables creates challenges and flexible operation of the synthesis unit incurs in additional costs, green plants typically decouple electrolysis from the Haber-Bosch section by buffering energy and intermediates mainly through hydrogen storage and/or batteries, keeping the synthesis loop closer to steady operation. Some demonstrators also include nitrogen and ammonia storage alongside the hydrogen storage [8], [9]. Before feeding the hydrogen to the synthesis loop, the electrolyser outlet undergoes the same basic conditioning steps described for the pink route [9].

Biomass-based ammonia production is typically discussed separately from green ammonia and labelled as bio-based or bio-ammonia, because hydrogen is derived from a biomass feedstock rather than electricity; however, in this thesis work, biomass-gasification route with or without CCS is classified as green [9]. The process follows a similar sequence to the brown route: the biomass is gasified to produce syngas that is then cleaned, shifted to increase the hydrogen content, and treated for CO_2 and sulphur removal before delivering a purified hydrogen stream to the synthesis loop (Figure 30) [8], [25].

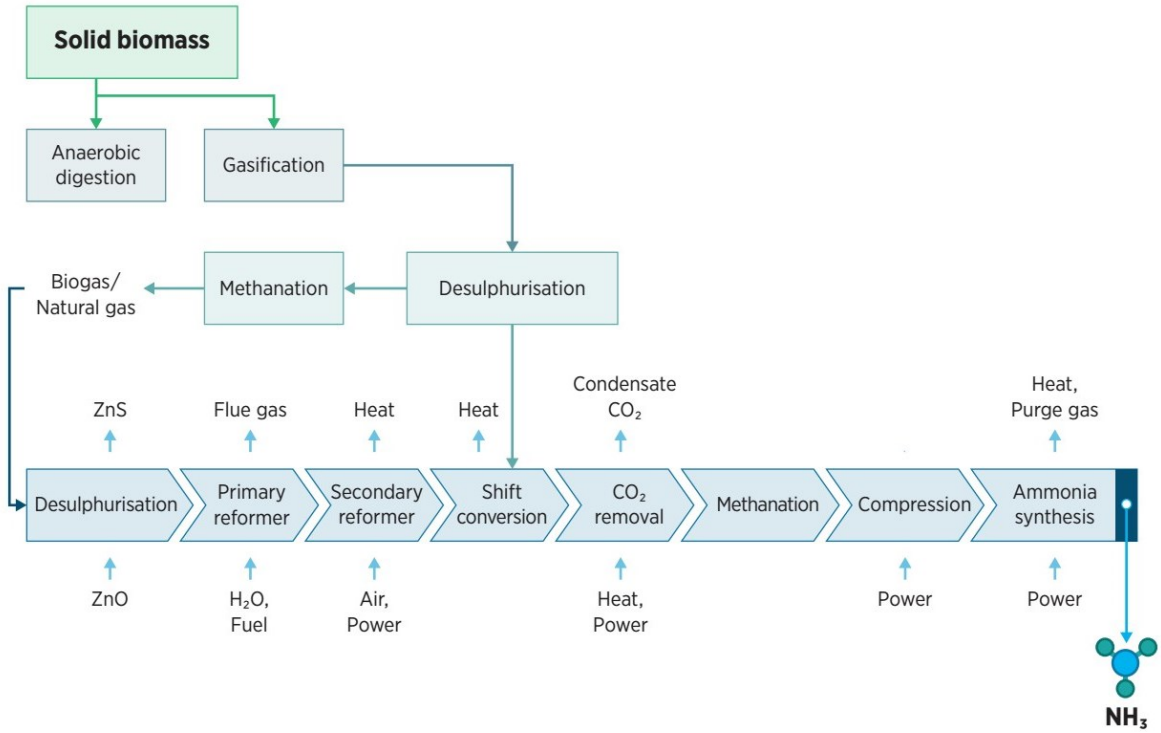

Figure 30 - Overview of steps used in ammonia production from biomass, either biogas or solid biomass, with embedded CO2 removal [9].

If CCS is not applied, the CO_2 separated in the conditioning section is released or potentially used on-site, whereas with CCS the captured CO_2 follows the same path described for blue production systems [8]. When biomass is harvested sustainably, this production route is the only one able, in principle, to deliver net-negative emissions on a life-cycle basis, especially when combined with CCS, because biogenic CO_2 is captured and permanently stored. Without CCS, biomass-based configurations can still achieve very low, and in some cases negative, operational CO_2 intensities (Figure 31), depending on the assumptions and system boundary adopted [6], [8].

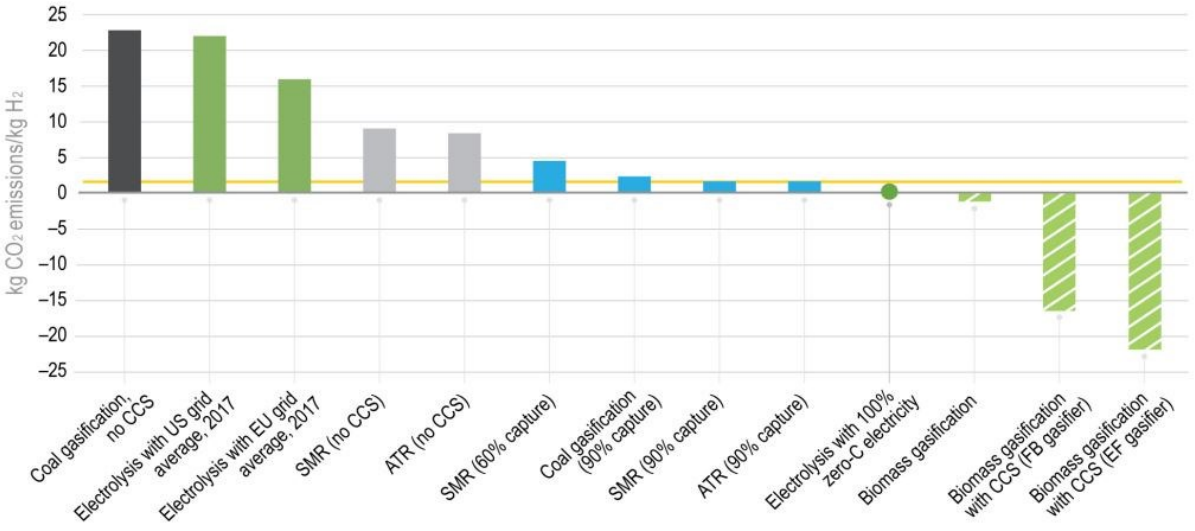

Figure 31 - Operational CO_2 intensities for different hydrogen production routes [8].

The yellow label is used in this thesis work to represent grid-powered electrolysis, although this colour is not applied consistently across the literature to describe the process. The rationale for this distinction is that, unlike other electrolysis-based processes, the indirect emissions of grid-connected hydrogen production depend strongly on the CO_2 intensity of the local electricity mix, which may vary significantly across regions and over time. The conditioning steps before feeding the hydrogen to the synthesis loop are the same described for other processes relying on electrolysis. Moreover, considering that the electricity supply is not limited to variable renewable generation, hydrogen storage is typically not required, although it may still be considered depending on plant design and operating strategy [8].

Brown and grey routes are fully industrialised, whereas the other options are characterised by lower and/or wider maturity range, because they require additional units and new integration challenges. Blue configurations maintain the same conventional hydrogen trains but extend the system boundary to include CO_2

conditioning, transport and permanent storage; although capture from concentrated process stream is described as mature, the full CCS chain is not widely deployed at full-scale, which is reflected by the lower TRL range. For turquoise pathways, even though the maturity range is lower, several projects are described as progressing toward commercialisation, with the International Energy Agency (IEA) reporting that the first commercial facility using methane pyrolysis-derived hydrogen is expected in 2025, whereas other announced projects are scheduled to come online by 2030. Electrolysis-based routes rely on conventional synthesis loop but shift the technology focus upstream to electrolysers and plant-wide integration at large scale, which is why the "full chain" is not yet as widely established as conventional fossil-based ammonia. Biomass gasification follows process steps analogous to coal gasification, but its application specifically in ammonia production is still described at prototype stage, which is reflected in the lowest TRL range among all routes [8].

Irrespective of these maturity/readiness gaps, recent project tracking indicates that the short-term deployment is dominated by low-emission projects rather than transitional ones (Figure 32).

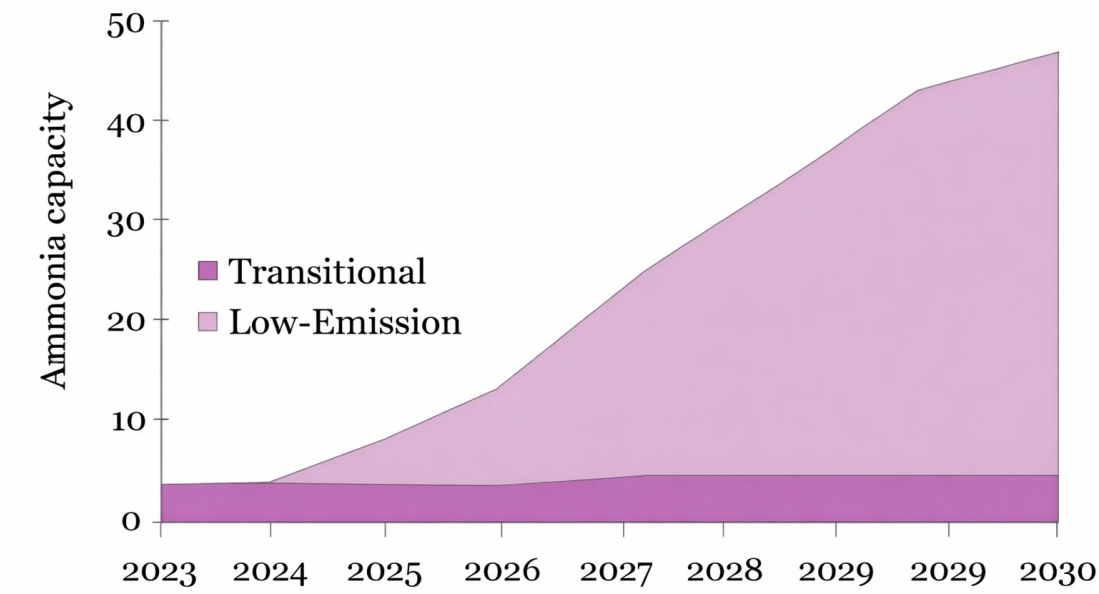

Figure 32 - Low-emission ammonia project pipeline expected this decade, split by maturity stage (operational, firm and mature) and category (transitional vs low-emission) [29].

In the Ammonia Energy Association (AEA) framework, low-emission includes pathways such as gas reformation with permanent CCS, water electrolysis and methane pyrolysis, whereas transitional covers lower-abatement configurations, for example byproduct fossil hydrogen and enhanced oil recovery pathways, that reduce emissions but are flagged as potentially not consistent with net-zero targets. Within

the subset of projects expected to reach operation this decade, the same dataset shows that capacity is concentrated in the two main technology pathways reported by AEA, namely gas reformation and water electrolysis, with a smaller residual share grouped as “other” (Figure 33).

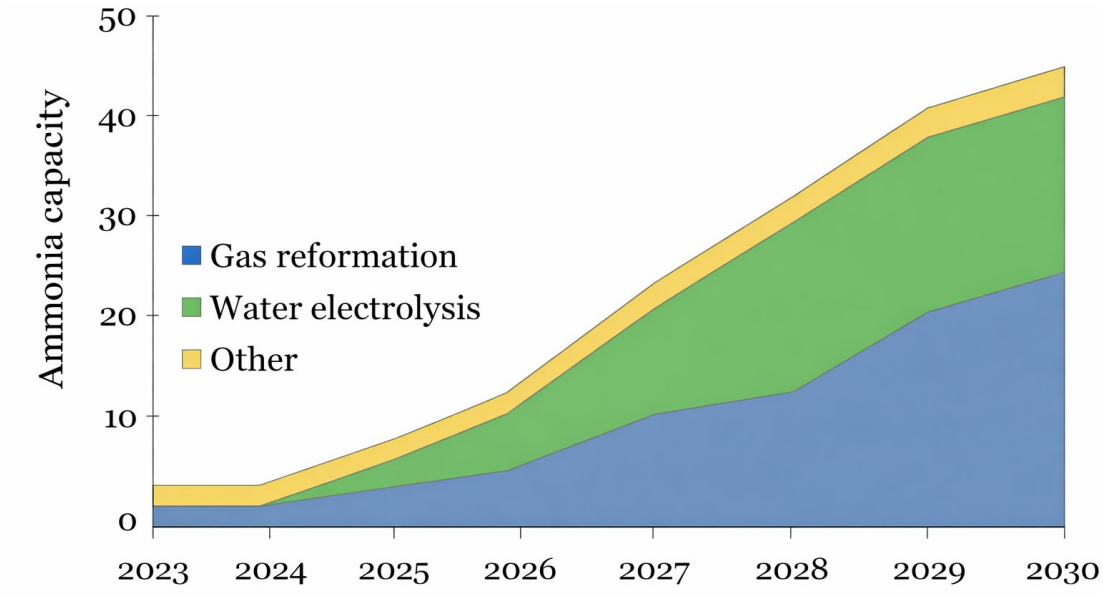

Figure 33 - Low-emission ammonia project pipeline expected this decade, split by maturity stage (operational, firm and mature) and technology pathway (gas reformation vs water electrolysis vs other) [29].

In AEA’s categorisation, gas reformation is a technology pathway that can include CCS, Carbon Capture and Utilisation (CCU) and Enhanced Oil Recovery (EOR) configurations, while water electrolysis aggregates projects that include electrolysis powered by nuclear, renewable and grid electricity.

This section establishes the common synthesis loop and a consistent colour-taxonomy for upstream hydrogen supply, which will be used as the basis for later comparisons of performance, emissions, and economics metrics in Section 0.

2.2 Innovative systems

Innovative systems are categorised as ammonia production concepts that go beyond fully standardised large-scale layouts, either by modifying conventional Haber-Bosch scheme for improved flexibility, modularity and integration with renewable electricity inputs, or by replacing the Haber-Bosch synthesis loop with alternative nitrogen-fixation routes [9], [30]. Analogously, the IEA groups early-stage/less mature options into technologies that retain or replace the Haber-Bosch process. Figure 34 highlights the contribution of these technologies, currently at market uptake or demonstration stage, to reach the emissions target of the IEA's Sustainable Development Scenario (SDS).

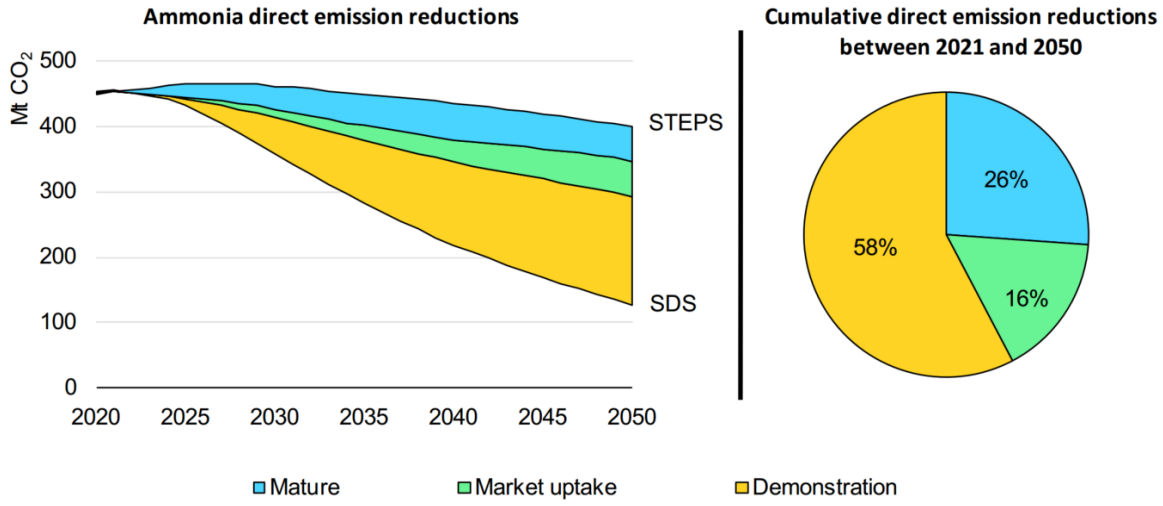

Figure 34 - Contribution of ammonia technologies to decarbonisation: evolution of annual direct CO_2 reductions and split of cumulative reductions (2021-2050) by technology stage under Stated Policies Scenario (STEPS) and Sustainable Development Scenario (SDS) [8].

Therefore, the first category remains based on the Haber-Bosch synthesis loop, but introduces operational innovations, for example targeting milder operating conditions, reducing temperature and pressure, and enabling a better integration with renewable electricity through modified process design [9]. In this context, the literature highlights that improved catalyst, enabling ammonia synthesis at lower temperatures and, in some cases, lower pressures, can increase process flexibility. However, as the operating pressure decreases, conventional ammonia separation by condensation becomes increasingly difficult, so more selective separation technologies for deep ammonia removal through enhanced sorbents become relevant as part of the overall loop design [31]. These sorbent-enhanced Haber-Bosch concepts use adsorption/absorption mechanisms to shift the equilibrium and enable operation at

less intense conditions; these features are reported as particularly relevant for small-scale, decentralised configurations (below 10 t/day), where conventional downscaling is challenging and improved flexibility and modularity are crucial coupling requirements with renewables to achieve a cost-effective scale-down. Pilot and demonstrator initiatives are explicitly reported as aiming to manage fluctuating energy inputs for renewable-ammonia synthesis, while validating catalysts and loop designs that can better tolerate variable operation (Figure 35) [9].

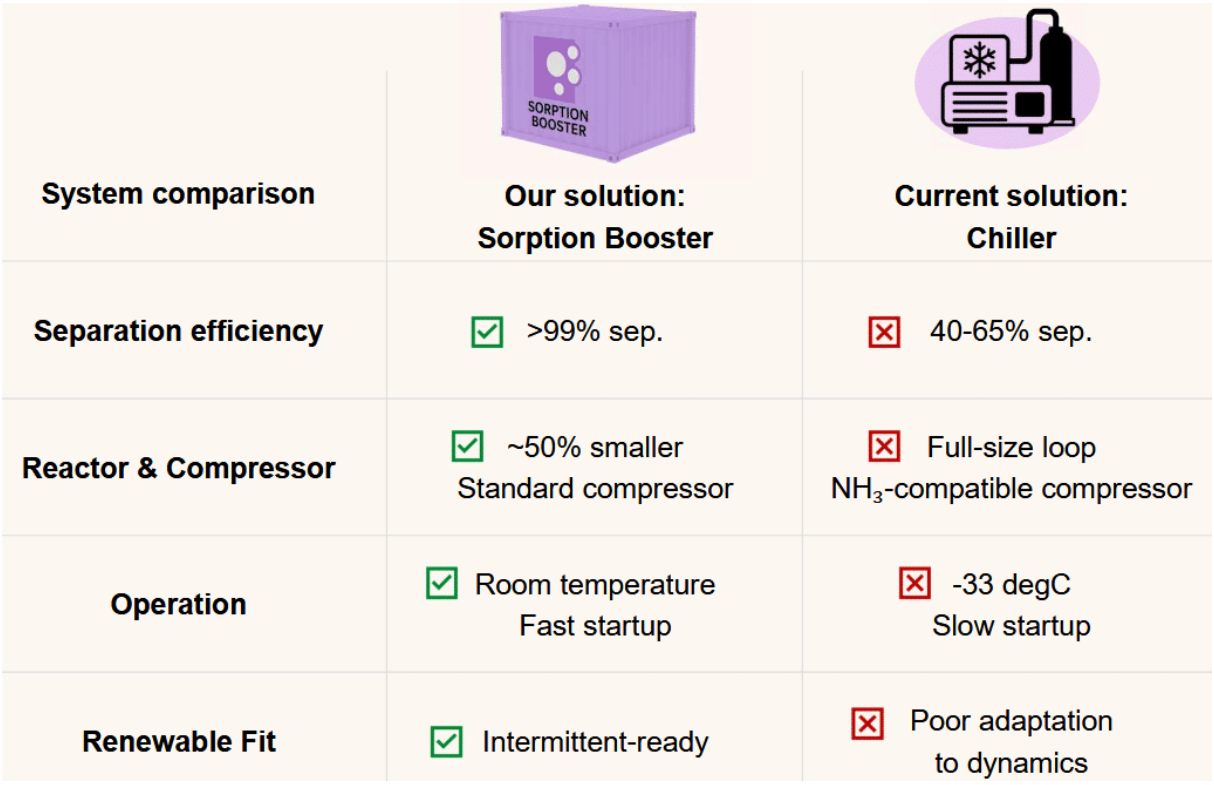

Figure 35 - Enhanced-sorbent solution using solid metal halide salts, developed by Ammisorb (start-up from the Danish Technical University) [31].

The second category includes non-Haber-Bosch routes, in which ammonia is produced using alternative processes that bypass the conventional sequence [30]. Non-Haber-Bosch routes represent a broad family of emerging nitrogen-fixation concepts covering electrochemical, photochemical, photoelectrochemical, plasma-based, chemical looping and biological pathways, and they are often presented alongside circular options such as ammonia recovery from waste streams [9], [30]. Since this set is highly heterogenous and largely at early/medium development stage, Table 5 reports the main technology families and associated representative process concepts considered in the literature, alongside their indicative TRL range.

Table 5 - Summary of non-conventional ammonia synthesis pathways and associated TRL estimates.

Energy input type	Process name	TRL	Ref.
Electrochemical	Electrochemical Nitrogen Reduction Reaction (ENRR)	3–5	[31]
	Lithium-mediated ENRR	1–3	[32]
Bio-electrochemical	Nitrogenase Bioelectrocatalysis	1–3	[33]
Electric (plasma-assisted)	Plasma-Catalytic	2–4	[34]
	Plasma–Electrochemical	3–5	[31], [35]
Thermochemical	Chemical Looping Ammonia Synthesis (CLAS)	4–5	[31], [36], [37]
Photonic	Photocatalytic nitrogen fixation	1–3	[38]
	Photo-Electrochemical (PEC) nitrogen reduction	1–3	[39]

Electrochemical ammonia synthesis uses electrical energy in an electrolytic cell to directly convert N_2 and a hydrogen source, typically water, into ammonia. This is achieved by conducting the Nitrogen Reduction Reaction (NRR) at the cathode of an electrochemical cell with specialised electrocatalysts [40]. For example, laboratory systems have demonstrated ammonia formation from N_2 and water using various catalysts, including approaches like lithium-mediated electrolysis, where Li metal formed in situ binds N_2 to form Li_3N, which then reacts with water to release NH_3 (Figure 36) [31], [32].

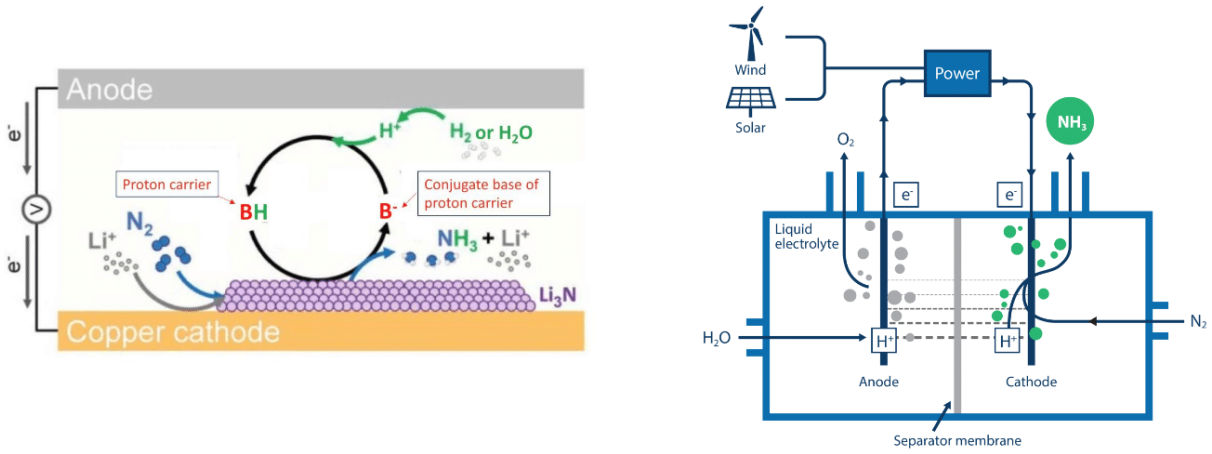

Figure 36 - Jupiter Ionics Lithium-mediated electrochemical ammonia synthesis [31].

The main advantages are the potential for operation at lower temperature/pressure than Haber-Bosch and the conceptual suitability for modular, flexible, distributed

production when powered by renewables [31], [40]. However, some challenges are still open, namely low selectivity, productivity and energy efficiency, because NRR competes strongly with the Hydrogen Evolution Reaction (HER) [40], [41]. Moreover, researchers must use isotope-labelled N_2 to confirm that ammonia is not arising from other reactions, generating false positives [31], [40], [42].

Despite being still at an early research stage, startup companies and academic groups are building prototypes that produce measurable quantities of ammonia. For instance, Atmonia (a university spin-off) has demonstrated laboratory-scale ammonia production using non-noble catalysts with isotope labelling validation, and multiple companies are targeting kg-per-day scale systems. Lithium-mediated electrochemical synthesis has achieved very high current-to-ammonia selectivity (Faradaic efficiency approaching 100%) in published studies, though scaling and engineering challenges remain [31], [32].

Bio-electrochemical ammonia synthesis is a hybrid approach combining biological nitrogen fixation with an electrochemical energy input. Nature's solution to breaking nitrogen's triple bond is the enzyme nitrogenase, found in select bacteria and archaea, which converts N_2 to NH_3 at near-ambient temperature and pressure. Nitrogenase is a complex enzyme system that requires a supply of electrons and significant metabolic energy in the form of ATP: the Fe protein delivers electrons to the catalytic MoFe protein coupled with MgATP hydrolysis, and this Fe-protein-dependent electron delivery is associated with the rate-limiting step of nitrogenase catalysis described in the literature. The idea behind the hybrid approach is to use an electrode to provide electrons to the enzyme (or to living microbes containing it), aiming to bypass the conventional Fe-protein/ATP-coupled electron delivery route. This could be done by immobilising nitrogenase on an electrode (directly or via mediators) or by interfacing with microbes in a bio-electrochemical reactor.

The fundamental advantage is that this enzyme-based conversion operates at near-ambient temperature and pressure while retaining biological specificity toward N_2 reduction, although productivity, energy input requirements, stability, and scale-up challenges must be addressed to reach commercial relevance. Therefore, this process category remains at an early research stage, with proof-of-concept demonstrations focusing on electron delivery strategies, immobilisation, and system stability rather than pilot-scale ammonia synthesis [33].

Plasma-assisted concepts employs non-thermal plasma (ionised gas) to activate nitrogen and promote its reaction with hydrogen sources. In a plasma reactor, electrical power, for example Alternating Current (AC) high voltage in Dielectric Barrier Discharge (DBD) systems, or Radio Frequencies (RF)/microwave power in

other discharges, generates a non-thermal plasma containing high-energy electrons, ions, radicals, and excited species, which can excite, ionise, and in some cases dissociate N_2, facilitating activation of the strong nitrogen triple bond at conditions far less severe than Haber-Bosch. The activated nitrogen species can then react with hydrogen, most commonly from H_2 feed; in some reported configurations alternative hydrogen-containing feeds, such as methane in microwave plasmas, have also been explored. Common designs include DBD reactors, glow discharge systems, and atmospheric-pressure plasma jets, and catalysts may be placed in the plasma zone or downstream to enhance NH_3 formation and improve selectivity (Figure 37).

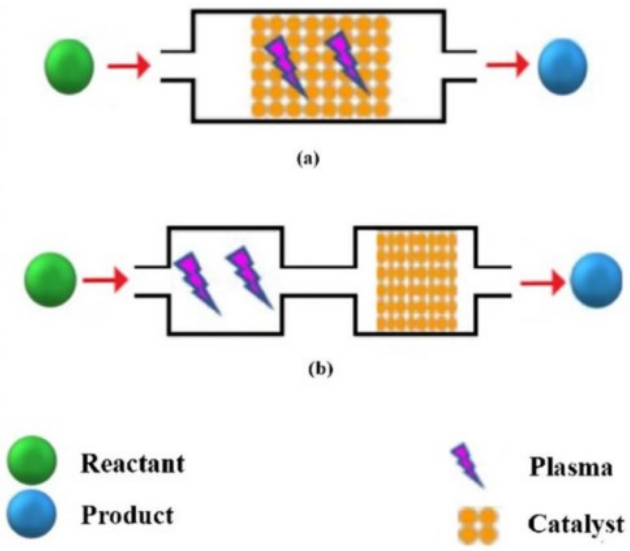

Figure 37 - Types of plasma-catalysis reactors with catalyst placed in the plasma-zone (a) or downstream (b) [34].

The main advantages are mild/near-ambient operation and, for DBD reactors in particular, simple construction and potentially low capital cost; plasma systems are also attractive where operational flexibility is needed to integrate variable electricity inputs. The key limitations are low energy efficiency and limited NH_3 yield, alongside potential, undesired by-products and scale-up challenges.

Despite its long history, dating back to early 1900s, this process is still under active development for optimisation and efficiency improvements. In recent years, interest has revived due to the need for flexible, small-scale ammonia production [31], [34].

A notable hybrid design combines a gliding arc plasma with an electrochemical cell: the plasma step converts air into NO_x and reactive nitrogen species, which are

subsequently electrochemically reduced to NH_3 to improve overall performance (Figure 38) [35].

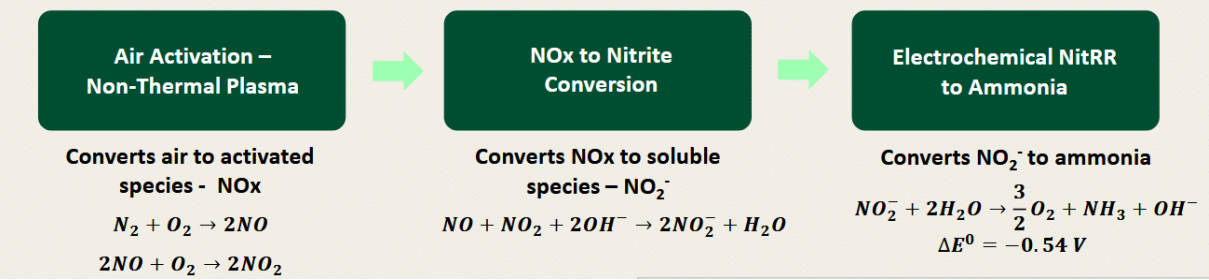

Figure 38 - GenCell's Ammonizer reaction steps
combining gliding arc-plasma based nitrogen oxides generation and electrochemical reduction [31].

Standalone plasma-catalyst reactors, including Ni-based and bimetallic systems, have demonstrated continuous ammonia production in laboratory-scale DBD reactors, and ongoing work focuses on plasma-catalyst synergy and reactor engineering to raise efficiency [34], [43].

Chemical Looping Ammonia Synthesis (CLAS) produces NH_3 through cyclic solid-gas reaction steps that separate nitrogen fixation from ammonia formation using a regenerable solid nitrogen carrier. The loop alternates between a nitridation step, where the carrier incorporates nitrogen, forming for example a nitride/imide, and an ammoniation/hydrogenation step, where the nitrogen-containing solid reacts with a hydrogen source to release NH_3 and regenerate the carrier, or a regenerable intermediate (Figure 39) [44].

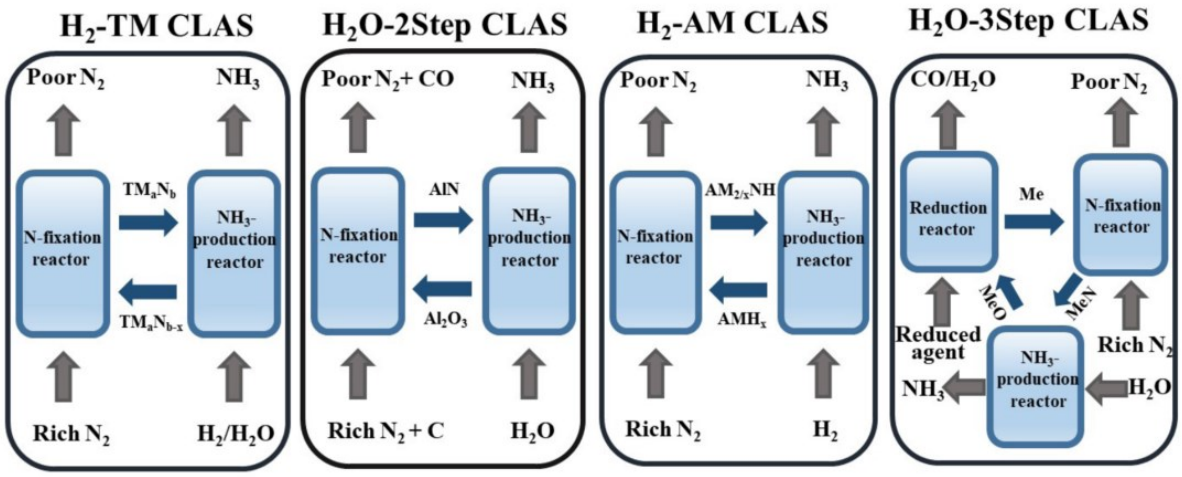

Figure 39 - Different configurations for CLAS [44].

By splitting the overall reaction into two or more steps, each sub-reaction can be optimised separately, avoiding the single-reactor compromise between N_2 activation and NH_3 synthesis.

This decoupling is commonly presented as a route to relatively mild operating conditions, including the possibility of low-pressure or near-atmospheric operation for nitrogen activation, and to flexible, potentially distributed process layouts compared to the conventional Haber-Bosch synthesis loop; however, multi-step process complexity and the need for durable carrier materials with favourable thermodynamics and kinetics over many cycles remain key limiting factors.

CLAS is widely regarded as a promising emerging alternative, but it is still largely in R&D/early prototype or pilot stages, with active research focusing on nitrogen-carrier families, such as transition-metal nitrides/imides, hydrides, composite carriers, and cycle designs, including detailed thermodynamic/kinetic screening and reactor/process optimisation [44].

In the Australian context, AMMONIAC is a research/development project on chemical looping ammonia production. Reported operating conditions are below 350°C and between 3-10 bar, with a 100 g_{NH_3}/day prototype demonstrated in early 2025 and 100 kg_{NH_3}/day specified as the next scale-up step; the same source highlights longer-term scale-up ambitions, with a 10 t_{NH_3}/day target (Figure 40) [31], [36].

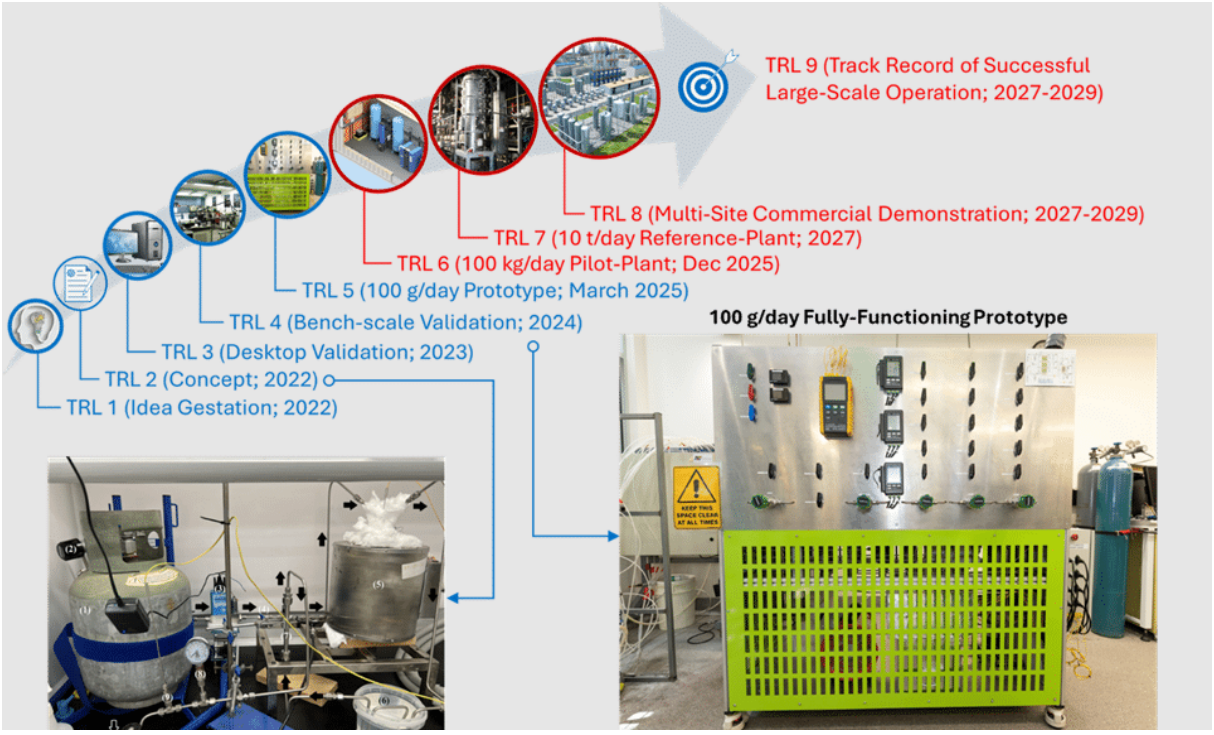

Figure 40 - Catalyst development in the AMMONIAC project [31].

Photonic ammonia synthesis refers to light-driven approaches such as photochemical, photocatalytic, and photo-electrochemical, that aim to produce ammonia by using solar energy to drive nitrogen reduction with a hydrogen/proton source, commonly water, under mild conditions. In photocatalytic nitrogen fixation, a semiconductor or a photoactive catalyst, absorbs photons and generates electron-hole pairs; photoexcited electrons can participate in N_2 reduction at the catalyst surface, while holes can drive an oxidation half-reaction, often involving H_2O or another donor. In Photo-Electrochemical (PEC) implementations, light absorption can be coupled explicitly to water oxidation to supply electrons for NRR, for example a bias-free pairing of N_2 reduction to NH_3 with H_2O oxidation to O_2 under solar illumination, is already demonstrated as a proof-of-concept.

Conceptually, this mimics artificial photosynthesis: sunlight is converted directly into chemical energy stored in NH_3, and in principle, the process can avoid fossil-derived H_2 and high-pressure operation. Researchers, therefore, focus on identifying catalyst families, typically semiconductor-based composites, that can activate N_2 under UV/visible light and improve charge separation/transfer to enable efficient hydrogenation to ammonia (Figure 41) [38], [39].

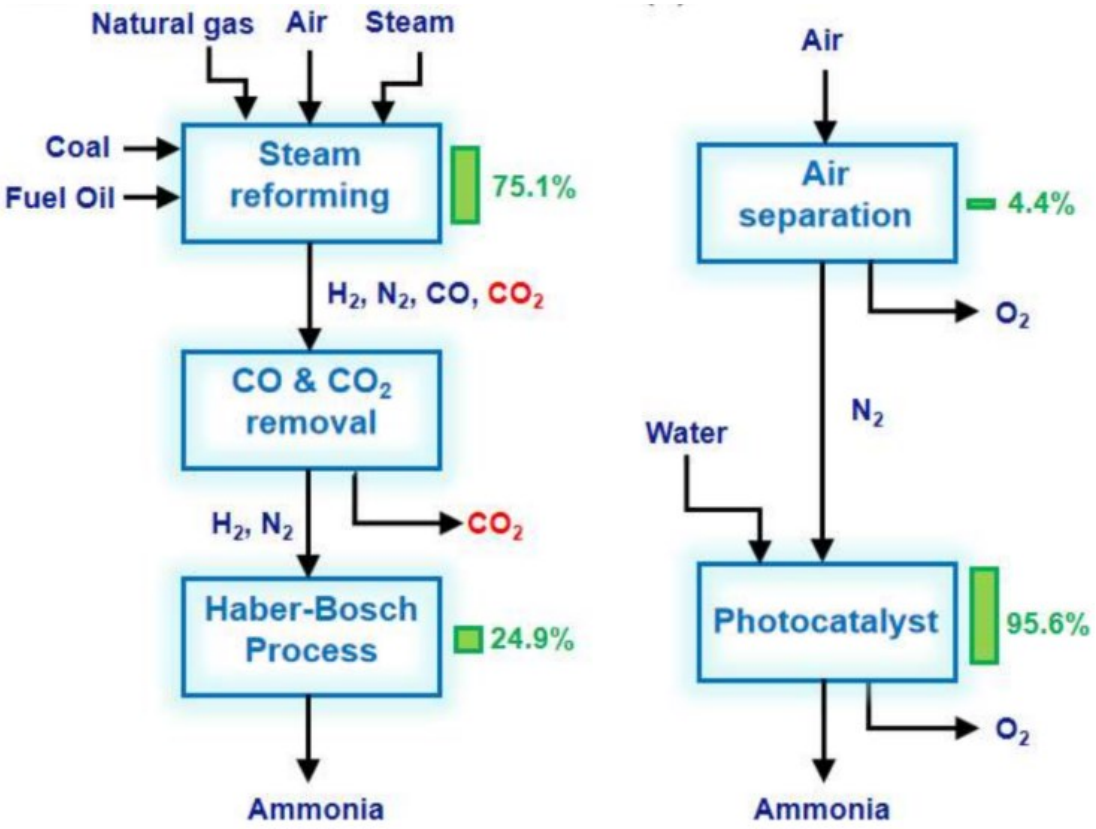

Figure 41 - Comparison of grey ammonia process and photocatalytic nitrogen fixation. Green blocks and number on the right represent the share of total energy input [38].

Despite the appeal of direct solar-to-chemical conversion, the literature emphasises that demonstrated rates/efficiencies remain very low and that substantial materials and mechanistic challenges for N_2 activation, selectivity, mass transfer, and reliable verification, still limit practical implementation; accordingly, the field remains at an early research stage dominated by catalyst classification and laboratory-scale studies rather than pilot-scale deployment [38].

3 The 3E analysis of conventional ammonia production

The 3E analysis (Energy–Environment–Economics) is an integrated approach to production system performance evaluation, with the goal of providing a full description of its energy efficiency, environmental sustainability and economic competitiveness [45].

This analysis is applied to conventional ammonia synthesis routes, based on the Haber-Bosch process reported in Section 2.1; therefore, all emerging production routes are excluded.

The research is done by collecting, processing and comparing data from scientific literature, as identified on Scopus with the following keywords: "Techno-Economic", "Thermodynamic" or "Life-Cycle Assessment" and "Haber-Bosch" or "Ammonia Production". A total of 26 are analysed [46]–[71].

The count of proposed plants in the investigated articles, by ammonia colour, is shown in Figure 42. Each ammonia production process contained in a single article is counted as 1 for each category, then the cumulative trend along the articles' publication years is obtained. This trend highlights a growing interest in blue and green ammonia in recent years with 11 and 16 articles focusing on these kinds of plants, respectively. Grey systems are reported in 17 articles; however, they are often treated as comparison benchmark for other processes, rather than being the focus of these studies. Notably, nuclear-based (pink) ammonia is consistently present throughout the entire time window and shows a gradual increase over time, while green ammonia remains relatively low in the early years and then grows markedly after 2020. The same can be said for yellow plants which are commonly used for comparative analysis with green/pink production plants, totalling 5 articles out of the 26. The interest about brown ammonia is limited, since it is geographically concentrated in China; also, turquoise production pathways show a moderate but still secondary interest in literature, with 6 articles, whereas pink totals 5.

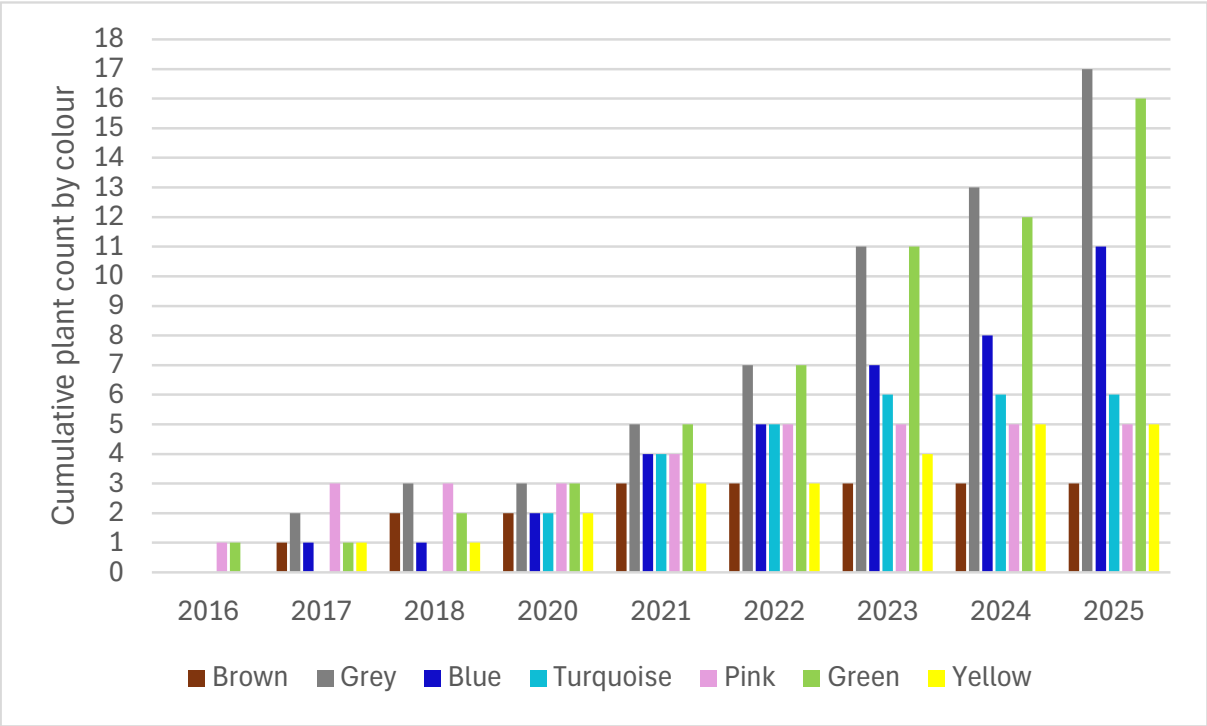

Figure 42 - Cumulative temporal evolution of production-plant counts by colour category, as reported in Scopus-indexed papers related to the 3E analysis (each year shows the cumulative total up to that year).

3.1 Methods

This section presents the methods followed for the 3E analysis and the related data collection procedure. The selected Scopus-indexed papers were systematically reviewed to collect plant-specific information within the 3E framework (Energy, Environmental and Economic). Data are extracted from the articles and mapped to the corresponding 3E dimension; when needed, the extracted information is further processed to obtain values that are comparable across studies. When values are not directly reported, because figures/graphs were insufficiently labelled and the text do not allow reconstruction of the values for each individual plant, data points are digitised using WebPlotDigitizer, ensuring consistency across heterogeneous sources.

Since 3E studies do not rely on a single unified, fixed set of indicators [45], the following sections 3.1.1, 3.1.2 and 3.1.3, introduce those adopted in this work for each dimension, together with the related data processing and the computations applied to harmonise datasets and enable consistent comparisons.

3.1.1 Energy dimension

The energy dimension indicators adopted are the Direct Specific Energy Consumption (DSEC) and the Specific Primary Energy Consumption (SPEC) to produce 1 t of ammonia. The former represents the process/plant efficiency by accounting for only the energy inputs required for the production plant ("first principle", within the plant boundary), whereas the latter reflects the system-level efficiency by converting the electricity component into the primary energy equivalent, thus incorporates upstream conversion and supply losses, while the chemical energy of fuels/feedstocks is reported on a Lower Heating Value (LHV) basis, therefore is already treated as primary energy within the adopted boundary.

DSEC is divided into components, such as chemical energy of the fuel used both for heat generation and feedstock for hydrogen production, electrical energy used by auxiliary equipment and electrolyser, and waste-heat used by thermo-chemical cycles or HTE which is typical for pink ammonia production.

These values are either retrieved directly from the articles, where explicitly provided, or computed for brown, grey, blue, turquoise and green ammonia derived from biomass gasification according to Equations (2), (3) and (4) :

$$DSEC_{ch} = \frac{\sum_i \dot{m}_i \cdot LHV_i}{\dot{m}_{NH_3,out}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (2)$$

$$DSEC_{el} = \frac{\dot{W}_{el,aux}}{\dot{m}_{NH_3,out}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (3)$$

$$DSEC_{tot} = DSEC_{ch} + DSEC_{el} \quad (4)$$

where the subscript i in Equation (2) stands for fuel and feedstock flows.

The LHV of the fuel and feedstock's flows is assumed 48 MJ/kg for natural gas (35.8 MJ/Nm^3 if the flow rate data are given in volumetric units) [72], unless a specific data is provided in the article. Where anthracite or bituminous coal are considered, the assumptions are 26.7 MJ/kg and 25.8 MJ/kg, respectively [73]. In some instances where only the fuel and feedstock composition is given, the LHV is computed following ISO6976:2016 indications [74]. Where energy integration systems are included in the plant layout, the eventual export of electricity to the grid is considered with a negative sign. In some cases, specifically for articles focusing on techno-economic analysis, the required values are not explicitly reported and only a range is provided, for example within sensitivity analyses on the Levelised Cost Of Ammonia (LCOA) as a function

of fuel/feedstock and electricity prices. To estimate the corresponding energy consumption indicators, the LCOA is first defined as the average unit cost of ammonia production over the plant lifetime, obtained by annualising the capital expenditure and adding annual operating costs, then dividing by the annual ammonia output according to Equation (5):

$$LCOA = \frac{CAPEX \cdot CRF + OPEX}{Q_{NH_3}} \left[\frac{€}{t_{NH_3}}\right] \quad (5)$$

where CAPEX is the total capital expenditure, CRF is the capital recovery factor, OPEX are the fixed and variable annual operating costs, and Q_{NH3} is the annual ammonia production in t/y.

Based on this definition, when sensitivity ranges are reported instead of explicit values, Equation (6) and (7) are used:

$$DSEC_{ch} = \frac{(1 + \Delta LCOA_{\%}) \cdot LCOA}{(1 + \Delta P_{i,\%}) \cdot P_i} \left[\frac{MWh}{t_{NH_3}}\right] \quad (6)$$

$$DSEC_{el} = \frac{(1 + \Delta LCOA_{\%}) \cdot LCOA}{(1 + \Delta P_{el,\%}) \cdot P_{el}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (7)$$

where P_i is the price of feedstock/fuel and P_{el} is the price of electricity.

Other techno-economic articles report the LCOA's cost breakdown, thus Equation (8) and (9) can be used:

$$DSEC_{ch} = \frac{CS_i \cdot LCOA}{P_i} \left[\frac{MWh}{t_{NH_3}}\right] \quad (8)$$

$$DSEC_{el} = \frac{CS_{el} \cdot LCOA}{P_{el}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (9)$$

where CS_i and CS_{el} are the share of fuel/feedstock source and electricity cost on LCOA, respectively.

For pink ammonia production plants using thermo-chemical cycles or HTE, the specific energy consumption is computed according to the following Equation (10), (11) and (12):

$$DSEC_{el} = \frac{\dot{W}_{el,aux} + \dot{W}_{el,HTE}}{\dot{m}_{NH_3,out}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (10)$$

$$DSEC_{th} = \frac{\dot{Q}_{th,HTE}}{\dot{m}_{NH_3,out}} \left[\frac{MWh}{t_{NH_3}}\right] \quad (11)$$

$$DSEC_{tot} = DSEC_{el} + DSEC_{th} \quad (12)$$

For green and yellow ammonia plants the equations are the same, with the only exception being that the LTE doesn't consume any thermal energy, therefore $DSEC_{tot}$ is equal to $DSEC_{el}$. When values are given with respect to the processed mass flow of an intermediate stream, for example, N_2 for the ASU or H_2 for the electrolyser, these are converted to a basis of ammonia production by using the appropriate stoichiometric relationships and molecular weights of the species, unless the corresponding data were explicitly provided in the article.

SPEC is computed by using an equivalent efficiency factor for electricity, depending on the source, in line with the conventions adopted by the IEA and technical literature. The average efficiencies of electricity generation from fossil fuels (coal, oil and gas) in the European Union (EU) in 2023 are reported in Table 6.

Table 6 - Representative efficiencies of fossil-based power generation technologies (EU-27).

Source	Efficiency	Ref.
coal	38.3%	[75] (*)
oil	39.0%	[75] (**)
gas	50.0%	[75], [76] (***)

(*) Average efficiency in 2019 computed directly from Eurostat data.

(**) Average value between 38-40%.

(***) Intermediate value between OCGT and NGCC.

Then the overall efficiency from fossil fuels is computed using the following Equation (13):

$$\eta_{fossil} = \frac{\eta_{coal} \cdot s_{coal} + \eta_{oil} \cdot s_{oil} + \eta_{ng} \cdot s_{ng}}{s_{coal} + s_{oil} + s_{ng}} \quad (13)$$

Where s_{coal}, s_{oil} and s_{ng} are the share of coal, oil and natural gas of total EU electricity generation in 2023. These values are 11.7% from coal, 1.4% from oil and 17.0% from natural gas, giving a total fossil contribution of 30.1% [77]. Eurostat's electricity and heat statistics confirm that the overall share of fossil fuels in EU electricity generation was approximately 31–32% in 2023 [78]. These steps were necessary to estimate the fossil fuel efficiency (45%), because the IEA no longer provides a single average fossil efficiency that is difficult to justify consistently, and now adopts the physical energy content method.

The conversion efficiency from primary energy to electricity for renewable sources and nuclear are assumed as 100% and 33%, respectively [79]. The average efficiency for grid electricity is computed according to the following Equation (14):

$$\eta_{grid} = \frac{\eta_{fossil} \cdot s_{fossil} + \eta_{ren} \cdot s_{ren} + \eta_{nuclear} \cdot s_{nuclear}}{s_{fossil} + s_{ren} + s_{nuclear}} \quad (14)$$

where s_{fossil}, s_{ren} and $s_{nuclear}$ are the shares of fossil fuels, renewables (wind, solar and hydro) and nuclear in EU electricity mix in 2023. These values are 30.1%, 41.1% and 22.8%, respectively, resulting in a grid efficiency equal to 66% [77].

Table 7 summarises all the values used for converting electricity into primary energy consumption. If an article does not state explicitly the electricity source used to feed the ammonia production plant, then it is assumed as fed by the grid. For those production plants with a net export of electricity to the grid, the electricity component is not converted into the primary energy equivalent.

Table 7 - Efficiencies of conversion from primary energy to electricity.

Source	Efficiency
fossil	45%
renewables	100%
nuclear	33%
grid electricity	66%

3.1.2 Environmental dimension

For the environmental dimension of the 3E analysis, Life Cycle Assessment (LCA) results are collected from peer-reviewed articles together with the main methodological descriptors, such as system boundary, impact assessment method, allocation approach, assumptions, and impact time horizon (where applicable). The purpose of this step is not to fully harmonise all environmental results, which is generally not possible across heterogeneous LCA methods and modelling assumptions, but to build a structured dataset framework that supports consistent interpretation and comparability where feasible.

The procedure follows three sequential steps:

1. For each article, a metadata table is compiled, reporting the main LCA methodological settings;
2. For each article, a database table is compiled, including all the LCA impact indicators reported in each study together with their units;
3. The resulting consolidated database is used to derive an occurrence matrix, which reports how frequently each indicator is available across the different ammonia production plants.

When results are directly comparable (same indicator name and compatible characterisation basis), reported values are converted, where needed, to a consistent impact unit and to the same functional unit. Conversely, when the same indicator label is associated with different units and/or different characterisation bases, the entries are kept separate, as they likely reflect different Life Cycle Impact Assessment (LCIA) methods and cannot be reliably harmonised. This choice avoids misleading cross-comparisons between indicators that are nominally similar but methodologically different.

Finally, for the subsequent discussion, the most significant indicators are selected based on their occurrence across plants and their overall coverage within the dataset.

3.1.3 Economic dimension

For the economic dimension, the analysis adopts the LCOA because it provides a single, normalised unit cost (€/t_{NH_3}) that enables direct comparison across plants and can be benchmarked against observable market prices. By contrast, Net Present Value (NPV), Pay-Back Time (PBT), and Internal Rate of Return (IRR) do not offer an equally transparent and universally applicable external reference value for cross-study comparison.

The economic analysis is carried out by initially collecting LCOA's values reported in literature for various conventional production plants, then actualising and converting into €$_{2025}$ according to the following Equation (15):

$$LCOA_{€_{2025}} = LCOA_{currency_{year}} \cdot AF_{year \to 2025} \cdot CF_{currency \to €} \left[\frac{€_{2025}}{t_{NH_3}}\right] \quad (15)$$

where the actualisation factors (AF) to 2025 are computed as the ratio between the September 2025 value and the annual average of the reference year. For the United Kingdom, the Consumer Price Index (CPI) from the Office of National Statistics (ONS) is used; for the United States, the Consumer Price Index-Urban (CPI-U) from Bureau of Labor Statistics (BLS); and for the Euro area, the Harmonised Index of Consumer Price (HICP) from Eurostat [80]–[82]. The currency Conversion Factors to euros (CF) are calculated as the September 2025 exchange rates, taken from the European Central Bank (ECB) datasets. For the British pound, the rate corresponds to the GBP/EUR series, while for the US dollar, to the USD/EUR series [83], [84]. Since the reviewed articles often adopt different economic assumptions, the collected values are normalised by applying a set of common assumptions, ensuring consistency in comparisons and further evaluations. Firstly, all the assumptions related to a carbon tax and additional streams of revenues other than ammonia are removed according to Equation (16):

$$LCOA_{clean,1} = LCOA_{article} - CT_{article} \cdot SE_{plant} + \sum_{i=1}^{n} Rev_{i,plant} \left[\frac{€_{2025}}{t_{NH_3}}\right] \quad (16)$$

where $CT_{article}$ is the carbon tax assumed by the article, SE_{plant} are the specific operative emissions of the production plant (t_{CO2}/t_{NH3}) and $Rev_{i,plant}$ are the revenues associated to streams other than ammonia.

Then, natural gas price has been harmonised using Equation (17):

$$LCOA_{clean,2} = LCOA_{clean,1} + \left(P_{ng,ref} - P_{ng,article}\right) \cdot DSEC_{ch} \left[\frac{€_{2025}}{t_{NH_3}}\right] \quad (17)$$

where $P_{ng,ref}$ is the reference gas price assumed for normalisation with a value of 11 €/GJ. It was derived from the Elenger Q1 2025 market overview, which reports front-month and forward prices around 40.7-43 €/MWh (corresponding to 11.3-11.9 €/GJ) for mid-2025 contracts [85]. The rounded value of 11 €/GJ was adopted as a cautious and representative value for 2025.

Finally, the plants with CCS are cleaned from specific assumptions on CO_2 transportation and storage costs and harmonised with a common assumption according to Equation (18):

$$LCOA_{clean,3} = LCOA_{clean,2} - Cost_{T\&S,CO_2,article} + Cost_{T\&S,CO_2,ref} \left[\frac{€_{2025}}{t_{NH_3}}\right] \quad (18)$$

A specific cost of 100 €/t_{CO_2} for transport and storage of captured carbon is adopted based on the SDE++ Aramis CCS Review, which identifies a range between 90.6-112.8 €/t_{CO2} in 2024 for full-chain CCS projects, reflecting typical investment and operational costs under current European conditions [86].

3.2 Results

This section reports the results of the 3E analysis, organised as box plots by plant category: highlighting both central tendencies and variability across technology families. Categories with limited sample size are reported for completeness but are not discussed in depth, as their distributions are not statistically robust.

Figure 43 illustrates the distribution of total DSEC for multiple ammonia production pathways.

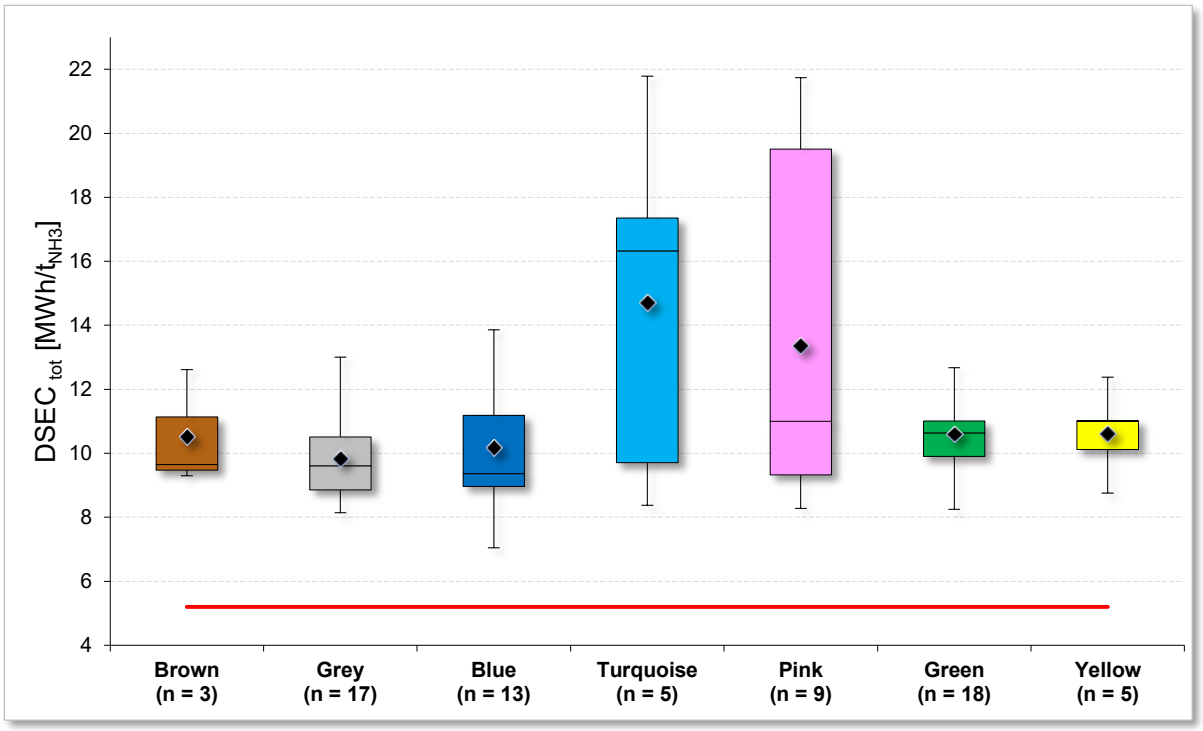

Figure 43 - Direct Specific Energy Consumption ("First Principle"),
n = sample size of each production pathway.
The horizontal line represents the LHV of ammonia converted into MWh/t (Table 1, Section 1.1).

Conventional routes (brown and grey) exhibit comparatively low average values (10.5 and 9.9 MWh/t_{NH3}, respectively) and a relatively narrow spread. This behaviour is consistent with their long-standing industrial maturity: having been deployed at scale for decades, these routes benefit from extensive incremental improvements, including heat integration, equipment optimisation, and overall process refinement.

When CCS is added to these plant configuration (blue), the average direct consumption increases (10.2 MWh/t_{NH3}). However, it is important to note that the underlying dataset includes CCS only for grey routes; if blue plants based on coal gasification were also included, the average may shift at higher values. This difference

is fundamentally associated with the additional energy demand of the capture chain and related utilities, which increase auxiliary loads even if the facility layout remains largely unchanged.

Among low-emission, but still fossil-based alternatives, turquoise ammonia shows the highest average value (14.7 MWh/t_{NH3}), reflecting the higher feedstock requirement per unit mass of ammonia produced, driven by reaction stoichiometry.

The pink category also presents elevated values and a wide range; however, this pattern is strongly influenced by the heterogeneity of the underlying sample. The category combines HTE configurations with thermo-chemical cycles. If the sample is disaggregated, HTE typically clusters at the lowest average values (9.6 MWh/t_{NH3}), while thermochemical cycles tend to occupy the upper end of the distribution (20.8 MWh/t_{NH3}) due to their substantial heat requirement, thereby increasing the aggregated mean and broadening the overall dispersion.

Green and yellow routes rely on the same LTE technology, so their direct specific consumption is practically equal (10.6 MWh/t_{NH3}). The key difference lies in the electricity supply: this choice does not change direct plant consumption, but it affects primary energy demand and thus system-level performance indicators.

In terms of robustness, the results for grey, blue and green are supported by larger and more coherent datasets, while those for pink and turquoise remain more uncertain due to limited data availability.

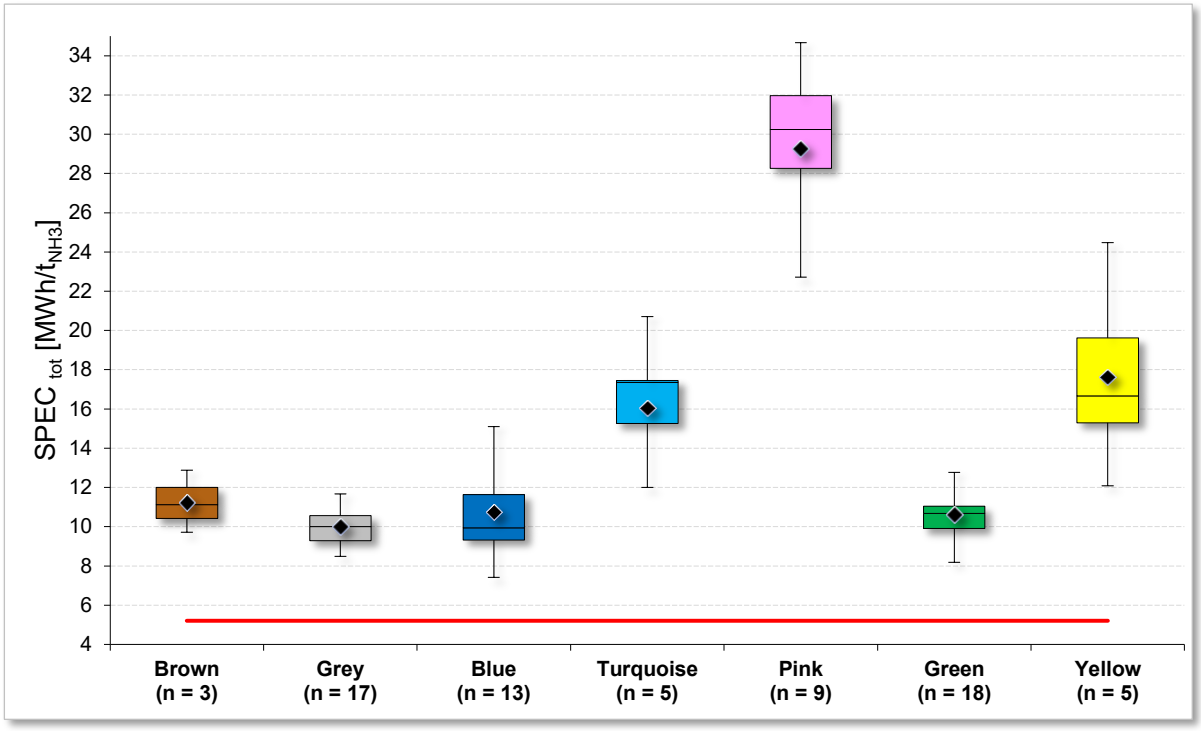

Figure 44 - Specific Primary Energy Consumption,
n = sample size of each production pathway.
The horizontal line represents the LHV of ammonia converted into MWh/t (Table 1, Section 1.1).

Figure 44 reports the total SPEC, which differs from DSEC because electricity is converted back to primary energy through an equivalent conversion efficiency. Under this convention, the green route remains essentially unchanged, since a 1:1 equivalence between primary energy and produced electricity is adopted.

Fossil-based pathways, both conventional (brown, grey) and low-emission options (blue, turquoise), show only marginal variations when moving from direct to primary energy, despite being penalised by a lower conversion efficiency. This limited change reflects the fact that their energy demand is dominated by the chemical energy of fuel and feedstock, while electricity represents a marginal share of the total.

The largest variation occurs for pink and yellow ammonia, whose energy balance is instead dominated by electricity and strongly penalised by the assumed efficiency used in the primary energy-to-electricity equivalence.

These two indicators provide a first-order picture of process efficiency, but they do not, by themselves, determine environmental performance: production routes with similar direct energy use may diverge once upstream burdens are accounted for, while electricity-dominated options can appear more or less favourable depending on the assumed supply mix and upstream supply-chain assumptions.

LCA impact indicators extend this discussion by translating energy and material inputs into environmental burdens within the defined system boundary, thereby capturing both direct and indirect contributions along the life-cycle. The environmental dimension of the 3E analysis is therefore addressed through LCA impact indicators, comparing environmental performances across each production pathway. Table 8 shows the main indicators selected for further discussion, along with a brief description and the main influencing drivers, while Table 9 reports the occurrence matrix of these indicators across each impact category. Appendix A reports the full spectrum of LCA impact indicators and their occurrences across different ammonia production pathways for the analysed articles.

Table 8 - LCA impact indicators adopted for the environmental dimension of the 3E analysis, including definitions/units and main drivers contributing to each category.

LCA Impact Indicator	Description	Main drivers
GWP_{100} [t CO_{2eq}]	Global warming potential over 100-year time horizon expressed as equivalent amount of CO_2.	Direct and upstream greenhouse gas emissions (CO_2, CH_4, N_2O, fluorinated gases), including energy supply chains.
ODP [g CFC-11_{eq}]	Ozone depletion potential, expressed as equivalent amount of CFC-11.	Emissions of ozone-depleting substances (CFCs/HCFCs/halons) and leakage during production and use.
HTP [kg 1,4-Db_{eq}]	Human toxicity potential, expressed as equivalent amount of 1,4-dichlorobenzene.	Chemical emissions, environmental fate and exposure pathways, and human health characterisation factors.
TAP_{100} [kg SO_{2eq}]	Terrestrial acidification potential over a 100-year time horizon, expressed as equivalent amount of SO_2.	SO_2, NO_x and NH_3 emissions, atmospheric transport, and deposition to soils and vegetation.
ADP [g Sb_{eq}]	Abiotic Depletion Potential for minerals and metals, expressed as equivalent amount of antimony (Sb).	Extraction and consumption of mineral resources, driven by material intensity and recycling rates.
FEP [kg P_{eq}]	Freshwater Eutrophication Potential expressed as equivalent amount of phosphorus (P).	Phosphorus emissions to freshwater from effluents, leaching and runoff.

Table 9 - Occurrence matrix of LCA impact indicators reported in the reviewed literature, for each conventional ammonia production pathway.

LCA Impact Indicator		Brown	Grey	Blue	Turquoise	Pink	Green	Yellow	LCA Impact Category
GWP_{100} [t CO_{2eq}]	Global Warming Potential over 100 years	3	12	11	4	1	20	4	Climate Change
ODP [g CFC-11_{eq}]	Ozone Depletion Potential	3	6	5	1	6	15	2	Stratospheric Ozone Depletion
HTP [kg 1,4-Db_{eq}]	Human Toxicity Potential	1	2	2	2	5	3	1	Human Toxicity (Total)
TAP_{100} [kg SO_{2eq}]	Terrestrial Acidification Potential over 100 years	3	5	2	1	1	12	1	Terrestrial/Freshwater Acidification
ADP [g Sb_{eq}]	Abiotic Depletion Potential	2	3	1	0	11	4	3	Abiotic Resource Depletion (Minerals/Metals)
FEP [kg P_{eq}]	Freshwater Eutrophication Potential	0	3	3	1	1	11	1	Freshwater Eutrophication

To improve data coverage for the brown and pink pathways, a limited number of results originally reported as GWP_{500} are harmonised and included alongside GWP_{100} values. This step requires an assumption because the GWP_{500}-to-GWP_{100} conversion is not unique and depends on the greenhouse emission mix (CO_2, CH_4, N_2O). Here, the harmonisation assumes CO_2-dominated profiles (≥90%), for which the difference between GWP_{100} and GWP_{500} is small and the conversion factor approaches unity [87], [88]. In Figure 45, the pathways for which GWP_{500} results are included and shown with an asterisk.

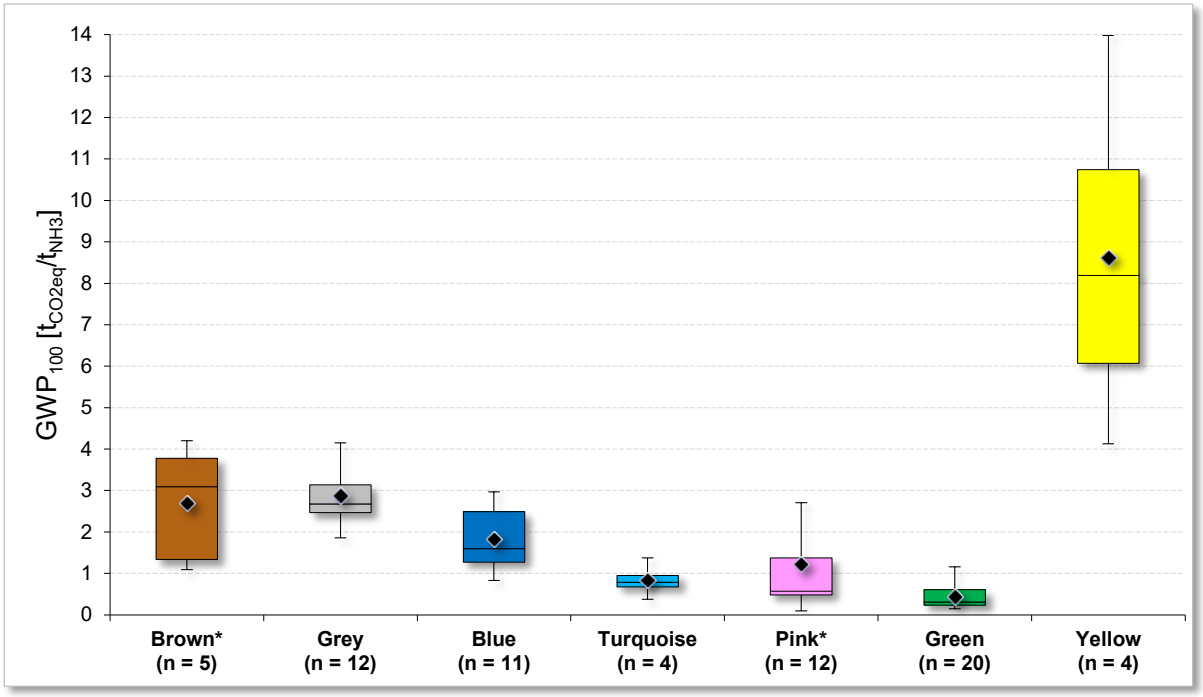

Figure 45 - LCA based Global Warming Potential over 100 years,
n = sample size of each Ammonia production pathway. *Includes GWP_{500} values (see text).

The brown pathway's mean appears broadly comparable with the grey route, and its dispersion suggests that some brown plants can reach performance levels overlapping with the blue distribution; however, this apparent behaviour should be interpreted cautiously, because it is largely driven by a small sample size and influenced by low-end points rather than reflecting the typical performance of coal-based systems, which is reported above 3 t_{CO2}/t_{NH3} by Mohamed et al. [30]. The two low values that pull down the distribution originate from Ren et al., which represents a methodological outlier within the reviewed sample. The study is developed by Shandong University and applies the "SDU" life-cycle impact assessment framework, including regionally adapted characterisation factors and China-specific background inventories, rather than more widely adopted LCIA methods and databases used in most of the other studies [58]. As a result, these modelling choices (impact method and background data) may alter the results and can plausibly explain why the corresponding brown values sit at the lower end of the distribution.

Consistent with this, the grey route clusters around 2.9 t_{CO2}/t_{NH3}, providing a useful benchmark for "unabated" fossil Haber-Bosch performance in the dataset.

Across the reviewed studies, the CCS capture parameter (reported as efficiency or capture yield) is typically around 90%, spanning between 85-95%; however, these values describe the potential reduction of direct, on-site CO_2 releases [48], [50], [53], [55]–[58]. In the LCA framework the net climate benefit is necessarily smaller because

CCS also introduces additional burdens within the system boundary, such as extra energy and supply-chain requirements for the manufacturing of CCS unit, capture, compression, leading to lower relative CO_2 emissions reduction for blue ammonia with an average value of 1.8 t_{CO2}/t_{NH3}, corresponding to a reduction of roughly 40%.

Turquoise ammonia appears in the lower spectrum of GWP_{100} average values in the dataset (0.8 t_{CO2}/t_{NH3}). This outcome is consistent with a system in which most carbon is handled in a way that avoids directs release to the atmosphere, so that residual climate impacts are primarily driven by upstream supply-chain contributions rather than large direct CO_2 emissions at the plant-level.

Pink ammonia generally falls below turquoise in the dataset, but three values drawn from Bicer et al. (originally reported as GWP_{500}), are comparable with brown ammonia, shifting the distribution upward [57]. At the same time, Mohamed et al. indicate that a more plausible central tendency for pink should lie between turquoise and green, consistent with a "clean electricity" pathway that is low-carbon but still retains non-zero upstream burdens [30].

The green route exhibits the lowest average value (0.4 t_{CO2}/t_{NH3}) and a relatively compact distribution. Since direct emissions from the synthesis tend to zero, the climate impact is again dominated by upstream contributions; therefore, variability across studies is largely explained by differences in the assumed power mix and modelling choices.

On the other hand, grid-powered electrolysis (yellow) displays the highest average value and the largest spread among the non-fossil categories shown. This pattern is expected for electricity-based routes supplied by a carbon-intensive or mixed grid: when hydrogen production is occurs through electrolysis; hence, the electricity-related emissions largely determine the overall climate impact; as a consequence, results are highly sensitive to the assumed grid intensity and can vary substantially across studies and regions, leading to a wider distribution.

Overall, the trend from grey to green ammonia is clear: as the hydrogen source shifts from fossils to renewables, the average GWP_{100} drops significantly from 2.9 to 0.4 t_{CO2}/t_{NH3}, while the distribution tightens, reflecting both lower emissions potential and improved stability across studies.

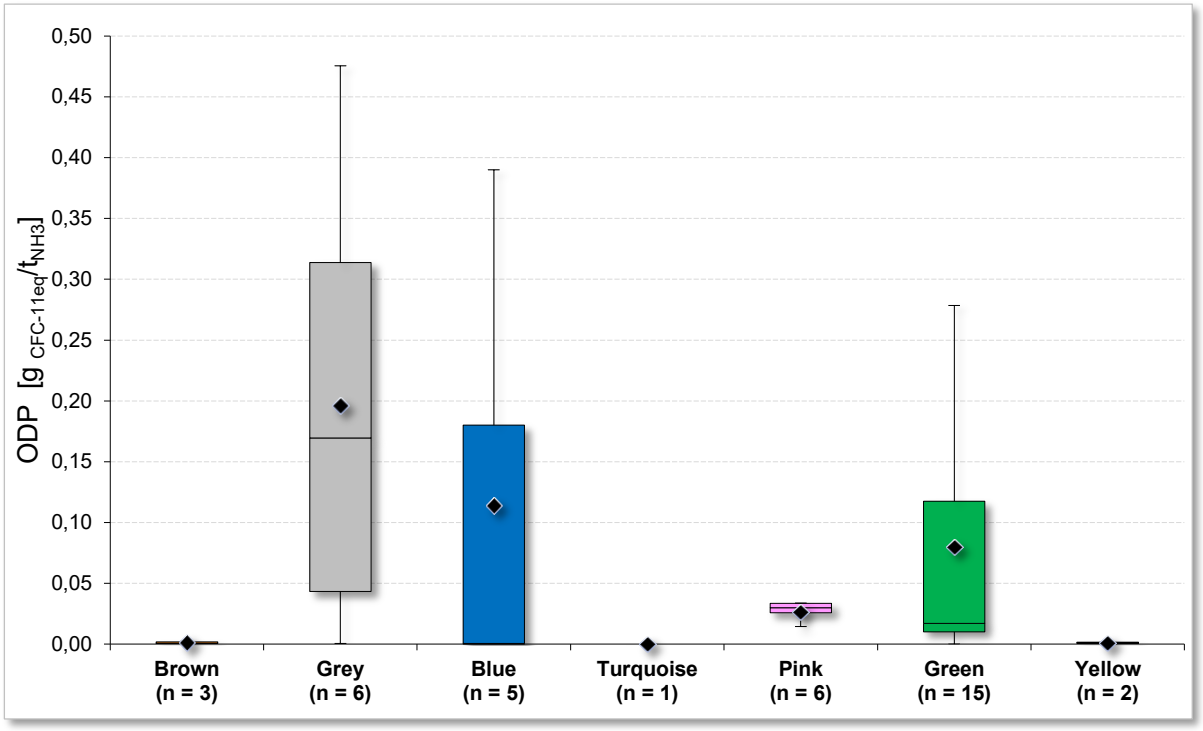

Figure 46 - LCA based Ozone Depletion Potential,
n = sample size of each Ammonia production pathway.

Figure 46, reports the ODP for different conventional ammonia production routes, which is primarily driven by ozone-depleting emissions occurring along the wider life-cycle inventory, including background supply chains and auxiliary services, rather than by the core ammonia synthesis itself. Consequently, pathway differences tend to reflect how background processes and auxiliary services are represented, and relatively small modelling differences can translate into visible shifts in the distributions.

Among the most robust categories, the grey route shows the highest average value (0.2 $g_{CFC\text{-}11}/t_{NH_3}$) and the largest variability, which is consistent with a fossil-based background that involves multiple upstream stages where ozone-depleting substances may arise indirectly, making ODP particularly sensitive to dataset choice and regional assumptions.

Blue ammonia sits at lower average value (0.1 $g_{CFC\text{-}11}/t_{NH_3}$) with a moderate spread, but it exhibits the lowest median among the main routes. This pattern suggests that most blue systems cluster at relatively low ODP, while a smaller subset of studies reports noticeably higher values, which is likely linked to how CCS-related auxiliaries are modelled, increasing the average without shifting the median to the same extent.

The green route shows a slightly lower average than blue (0.08 $g_{CFC\text{-}11}/t_{NH_3}$), yet its median exceeds the blue one, and the distribution remains appreciably dispersed. This

combination is consistent with a set of very low ODP cases, pulling the mean downward, while differences in electricity-supply and background inventories keep the central portion of the dataset at a higher level.

Pink ammonia appears as the lowest ODP option in the current dataset (0.03 $g_{CFC\text{-}11}/t_{NH_3}$) and shows a tight distribution. Although the sample size remains limited, the narrow spread suggests that the available studies adopt broadly consistent assumptions, resulting in closely aligned outcomes.

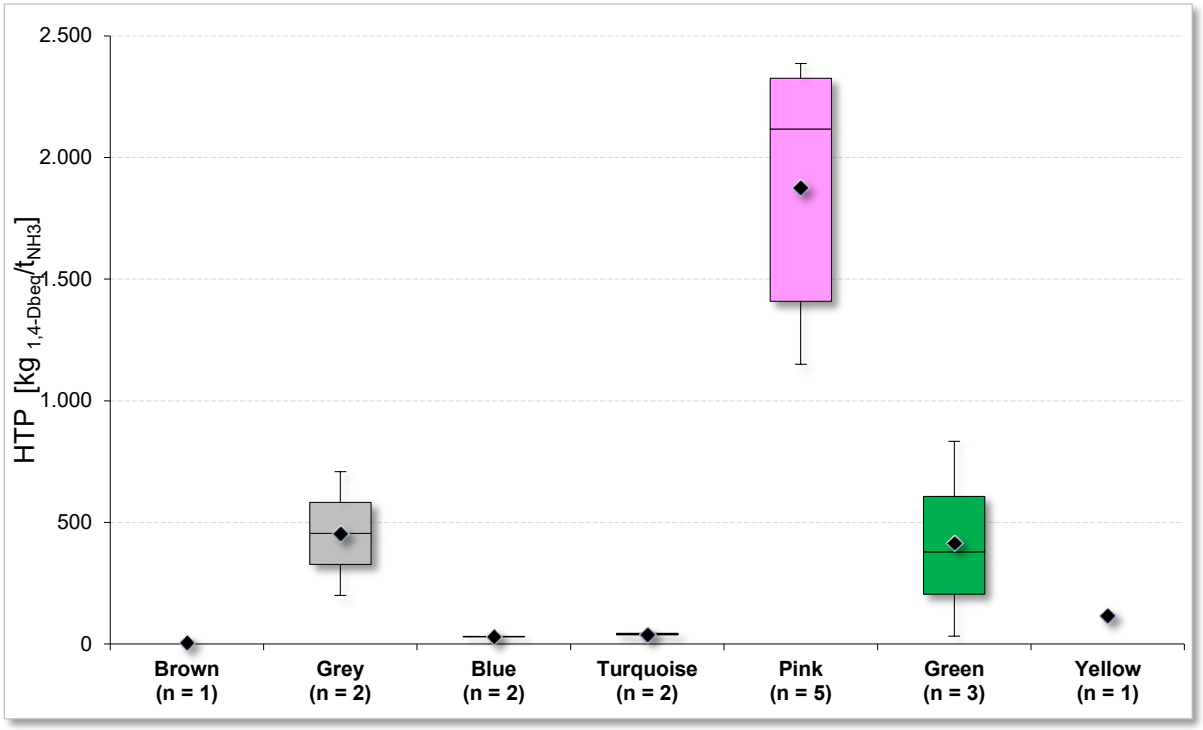

Figure 47 - LCA based Human Threat Potential,
n = sample size of each Ammonia production pathway.

Figure 47 reports the HTP, which is mainly driven by toxic releases along the life-cycle, their environmental fate, and exposure/toxicity characterisation. Consequently, this category is typically sensitive to inventories and can vary substantially across studies.

Within the fossil-based routes, grey systems exhibit a high average value (454 $kg_{1,4\text{-}Db}/t_{NH_3}$) and a broad distribution. Although the sample size is limited, the position of both mean and median indicate that grey remains consistently elevated within the available data.

Pink ammonia stands out with the highest average value (1878 $kg_{1,4\text{-}Db}/t_{NH_3}$) and the widest overall range. Moreover, the median exceeds the mean, suggesting a distribution where very high values are common, while few data pull the mean

downward. This pattern is consistent with a technology group that aggregates heterogeneous configurations and backgrounds; in such cases, differences in upstream assumptions, as well as the modelling of electricity and materials, can strongly influence toxicity-related indicators. Moreover, part of the HTP signal can plausibly originate from upstream fuel-cycle stages (uranium mining, milling, and fuel processing) and associated material and waste-management chains, which contribute toxic releases captured by the life-cycle inventory.

The green route shows a much lower average than pink, but still comparable with grey (415 $kg_{1,4\text{-}Db}/t_{NH_3}$), while retaining a considerable spread. In this case, the mean slightly exceeds the median, which suggests that a subset of higher-impact systems lift the average. This behaviour is coherent with an electricity-dominated pathway: HTP is strongly dependent on how the electricity supply chain and background datasets represent emissions and toxic substance flows, leading to meaningful dispersion across studies even when the foreground process is similar.

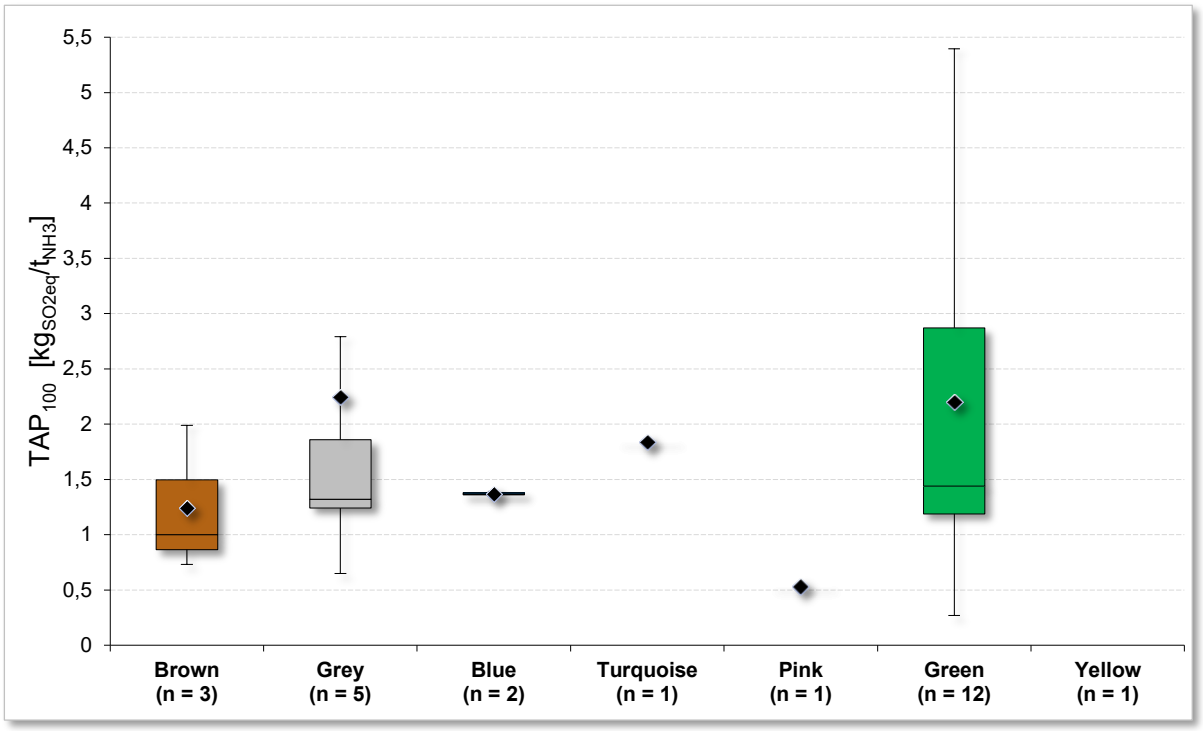

Figure 48 - LCA based Terrestrial Acidification Potential over 100 years,
n = sample size of each Ammonia production pathway.

Figure 48 reports TAP_{100}, which reflect the potential for terrestrial acidification and is mainly driven by SO_2, NO_x, and NH_3 emissions, together with atmospheric transport and deposition. This means that the indicator is typically influenced by upstream

combustion-related emissions (SO_2/NO_x) and how plant-level NH_3 leakage/slip are represented in the inventory.

Among the statistically more robust groups, the brown route shows a relatively compact distribution with a moderate average value (1.2 kg_{SO_2}/t_{NH_3}). This suggests that, within the reviewed studies, coal-based configurations lead to broadly comparable acidifying emissions once the main combustion and flue-gas control assumptions are set.

Grey ammonia exhibits a similar median, compared to brown, but a higher average (2.3 kg_{SO_2}/t_{NH_3}) and a more dispersed distribution towards high values. This pattern is consistent with TAP_{100} being highly sensitive to upstream assumptions: a subset of studies likely includes higher SO_2 and/or NO_x burdens from fuel supply and/or less favourable emission-control representations, and/or higher NH_3 leakage/slip assumptions, which lifts the mean while the median value remains closer to the central cluster.

The green route shows an average value (2.20 kg_{SO_2}/t_{NH_3}) that is comparable to, or slightly higher than the fossil routes, but it also displays the largest spread among the statistically meaningful categories. This wide dispersion indicates that acidification in electricity-dominated routes is strongly dependent on the assumed electricity supply-chain: power systems with higher SO_2/NO_x intensities (or different air-pollution control profiles) translate into markedly higher TAP_{100}, whereas cleaner mixes push results toward the lower end. At the same time, any NH_3 slip/leakage included within the plant boundary can further vary this indicator, reinforcing that it is influenced by both grid-related emissions and site-specific inventory choices.

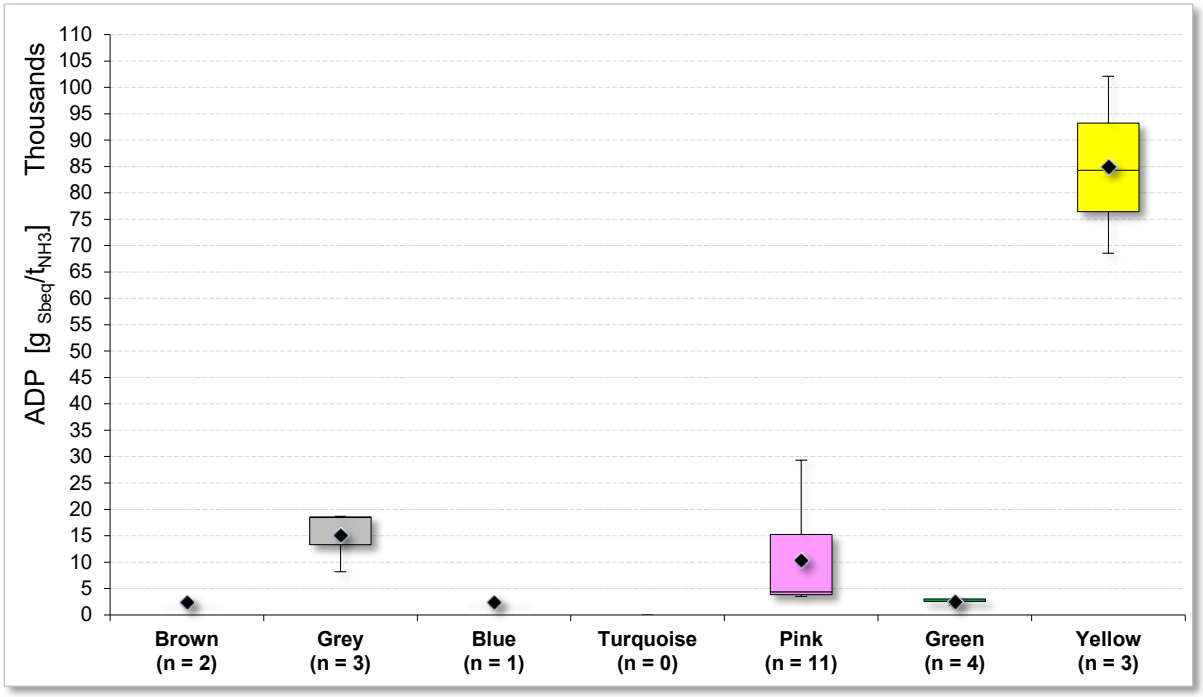

Figure 49 - LCA based Abiotic Depletion Potential,
n = sample size of each Ammonia production pathway.

Figure 49 reports ADP of minerals and metals, which is primarily driven by material intensity across the life cycle, as well as assumptions on supply chains and recycling. Unlike climate indicators, ADP does not necessarily track fuel consumption directly; instead, it responds to how "hardware-heavy" the pathway is in the foreground and, especially, in the background system.

Within the fossil-based routes, grey shows a relatively high average value (15100 g_{Sb}/t_{NH_3}) with a distribution that remains elevated even though the sample size is limited. This suggests that, for the available studies, mineral and metal requirements associated with this pathway's upstream system and its supporting infrastructure constitute a non-negligible burden.

Pink ammonia exhibits the largest spread and a relatively large average value (10426 g_{Sb}/t_{NH}). The fact that the mean is far above the median indicates that most pink cases cluster at comparatively moderate ADP, while a subset of scenarios reports very high values, pulling the average upward. This behaviour is consistent with technology heterogeneity and, more importantly for ADP, with large differences in assumed material requirements and background modelling choices, for example in how nuclear-related infrastructure, construction materials, and end-of-life/recycling assumptions are represented.

The green pathway shows the lowest and tightly clustered ADP signal (2528 g_{Sb}/t_{NH_3}). Overall, the limited spread suggests that, across the reviewed studies, green ADP is

less affected by extreme infrastructure assumptions than pink, even though both rely on electricity-based hydrogen production.

In contrast, the yellow route stands out with by far the highest average value (84995 g_{Sb}/t_{NH_3}). This result points to a pathway that is strongly penalised in mineral and metal depletion, plausibly due to the combination of electricity supply-chain burdens and/or highly material-intensive upstream configurations represented in those articles. Even with a small sample size, the separation from the other pathways is sufficiently large to suggest a structurally different profile.

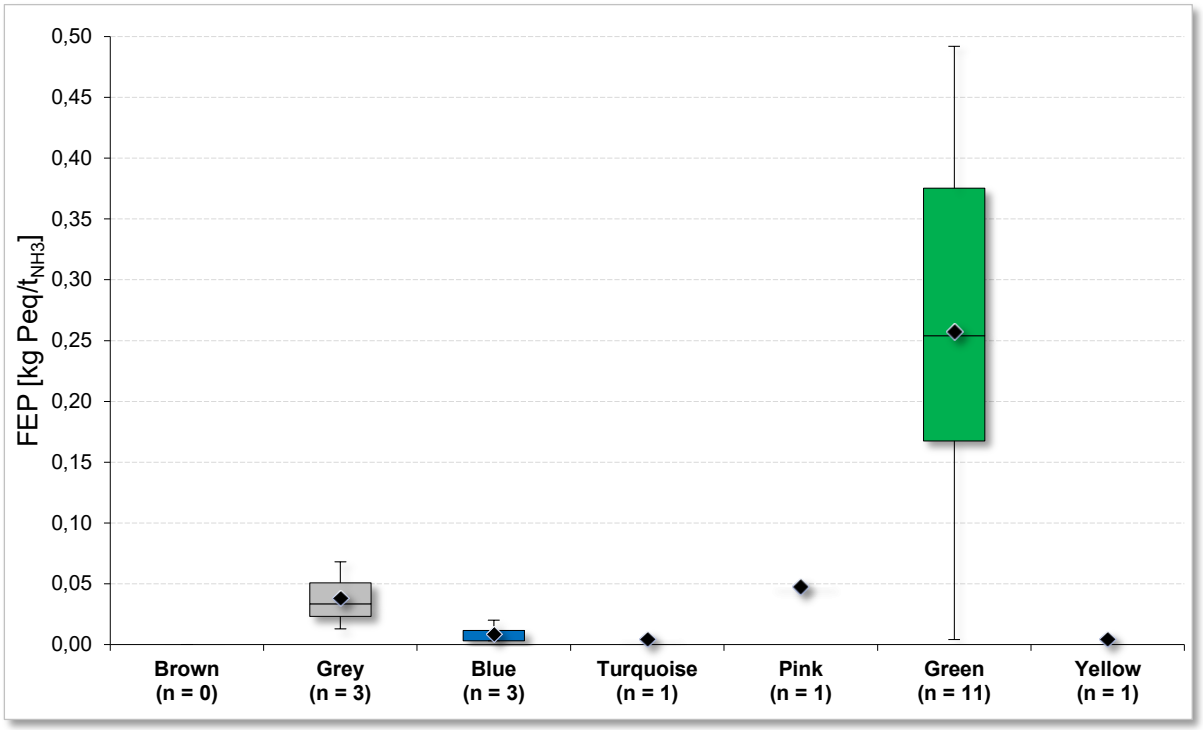

Figure 50 - LCA based Freshwater Eutrophication Potential,
n = sample size of each Ammonia production pathway.

Figure 50 captures FEP, which is primarily driven by phosphorus releases to freshwater occurring along the life-cycle, including effluents, leaching, and runoff associated with upstream processes and their supply chains. For ammonia production pathways, this category is therefore less linked to the synthesis loop itself and more sensitive to upstream industrial supply chains and to how waterborne emissions are represented in background inventories.

Within the robust fossil-based categories, grey shows a moderate average value (0.038 kg_P/t_{NH_3}) with a relatively compact distribution, suggesting that, across the

reviewed cases, eutrophication burdens remain limited and are mainly shaped by upstream processes rather than by large direct phosphorus discharges at the plant.

Blue ammonia displays a lower average and a tight distribution (0.0087 kg_P/t_{NH_3}). This clustering indicates that, in the reviewed inventories, adding CCS does not introduce substantial freshwater eutrophication burdens; instead, FEP remains governed by background processes whose contributions are relatively similar across the available studies.

In contrast, the green route shows by far the largest average value (0.258 kg_P/t_{NH_3}) and the widest variability. This behaviour indicates that FEP for electricity-based hydrogen routes is strongly context-dependent and can be dominated by the upstream electricity supply-chain and associated industrial activities in the system. As a result, green FEP can range from very low values to comparatively high outcomes depending on the assumed power mix and database representation of waterborne emissions, leading to a broad variability.

The following comments complement the energy and environmental comparison with the economic dimension, reporting LCOA values and highlighting how harmonisation of assumptions affects the interpretation of competitiveness across routes.

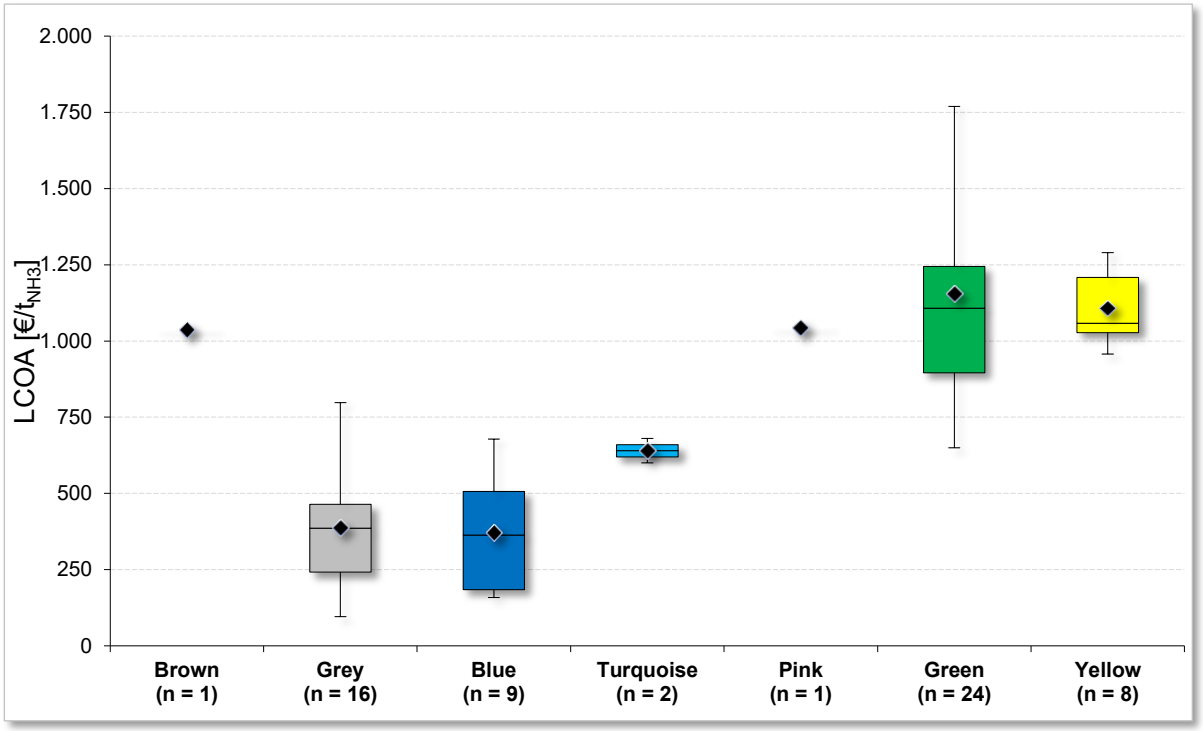

Figure 51 - Levelised Cost of Ammonia actualised and converted as reported in Section 3.1.3, n = sample size of each production pathway.

The comparative analysis of the various production routes based on LCOA updated to €$_{2025}$/t_{NH_3} (Figure 51) yields a quite clear stratification, although there is some overlap between different production routes: grey and blue occupy the lowest cost ranges with broadly overlapping distributions. Somewhat surprisingly, the grey route has a slightly higher mean and median cost than blue, which is related to the optimistic assumptions made in different underlying studies that include different carbon pricing mechanisms, very low natural gas prices and neglect or underestimate transport and storage costs for captured CO_2. All these factors may strongly bend the apparent competitiveness between unabated and CCS-equipped systems.

Turquoise sits in an intermediate position, consistent with the additional costs of methane pyrolysis units and solid carbon handling. At the top end, green and yellow display the highest values of LCOAs, with green showing a much broader spread. This variability reflects the strong sensitivity of electrolysis-based routes to electricity prices, electrolyser investment costs, capacity factors, financial assumptions and the need for additional storage unit to buffer the variability of electricity supply. Yellow shows a slightly lower and more compact distribution but is still costly for the same reasons.

Brown and pink ammonia show similar LCOAs to the green and yellow ammonia, however those series have only one data point and lack statistical robustness. In general, the results show that fossil-based technologies remain economically more competitive, while electricity-based routes show a larger spread and higher central values.

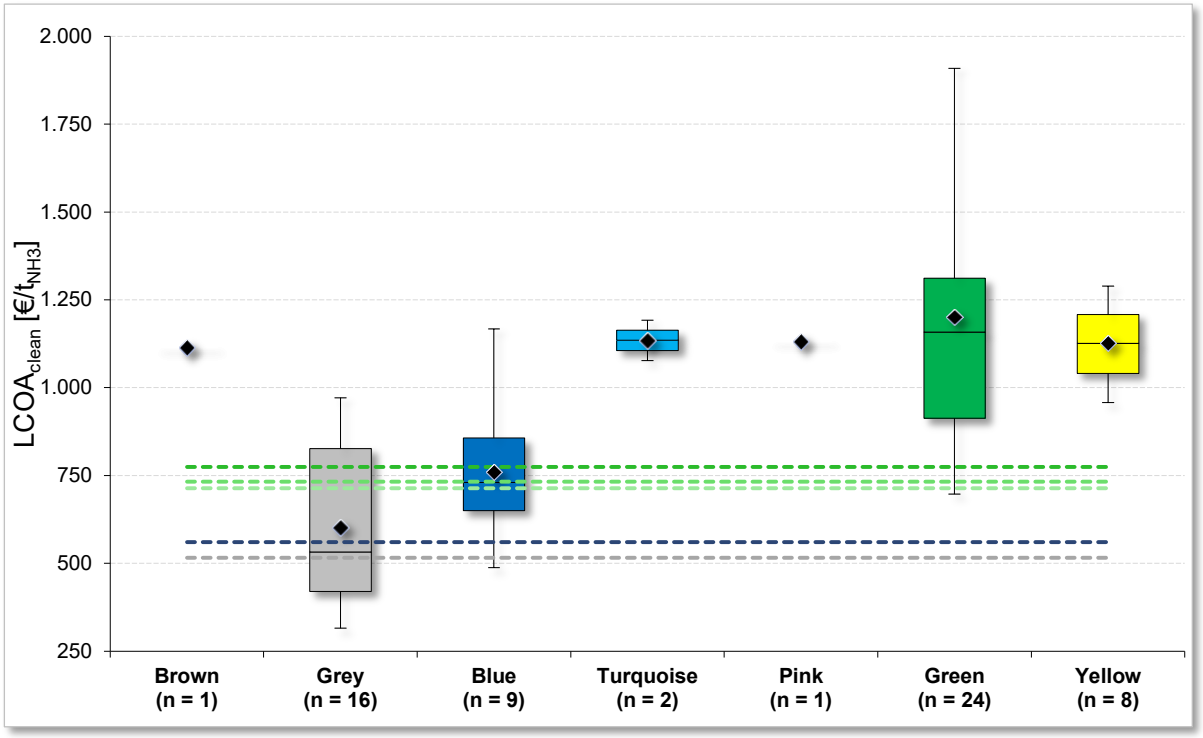

Figure 52 - Levelised Cost of Ammonia cleaned from assumptions as reported in Section 3.1.3, n = sample size of each production pathway.
Horizontal lines represent the price of ammonia for September 2025 (see Section 1.3)

The LCOA comparison harmonised for carbon pricing, additional revenue streams, natural gas price assumptions, as well as with standardised CO_2 transport and storage costs for blue (Figure 52), provides a much more coherent picture of the levelised cost of each of the conventional ammonia production routes. In addition, the horizontal lines provide a direct price benchmark and enabling a clearer interpretation of cost-competitiveness under consistent accounting

In this harmonised comparison, the cost relationship between grey and blue assumes its expected order, with grey coming out as the lowest-cost option and blue showing a higher median and average value. This result represents the intrinsic energy and capital penalties related to CO_2 capture, compression, and storage. The previous inversion seen in the unadjusted data was primarily related to the product of differing assumptions on carbon pricing, natural gas costs, and crediting of additional revenue streams. Once these are normalised, the results better reflect underlying techno-economic fundamentals, confirming that CCS integration raises production costs, although the gap between grey and blue remains moderate under consistent assumptions.

Turquoise and brown ammonia fall within the upper range of the fossil-based routes, both exceeding 1000 €/t with the pink route sharing similar LCOA, although all these

production routes lack statistical robustness. At the higher end of the spectrum, green and yellow continue to exhibit the largest cost levels: green ammonia shows the widest variability, reflecting its strong sensitivity to assumptions on electricity prices and electrolyser capital costs, while yellow remains slightly lower in median and average value but similarly influenced by its reliance on grid electricity and its cost.

These benchmarks show that, under harmonised assumptions, only grey ammonia fall consistently below or near market prices, while all low-carbon and renewable routes remain above the market range, indicating the persistent economic gap to be bridged through technological learning or supportive policy instruments. More precisely, grey overlaps with its benchmark in the central range, whereas blue and green price benchmarks align mainly with the lower tail of their respective distributions; therefore, closing the gap requires either best-in-class project conditions or additional support mechanisms. Across the energy indicators, DSEC values show limited separation among most routes because they capture direct plant energy use, whereas SPEC exhibits stronger differentiation for electricity-dominated pathways due to the assumed primary energy-to-electricity equivalence; therefore, SPEC rankings remain contingent on the convention adopted. Across environmental indicators, no single ammonia production route is consistently best across all LCA impact categories. While shifting from fossil-based hydrogen to low-carbon or renewable options can reduce life-cycle greenhouse gas emissions, other impact categories may worsen, highlighting the need to include multiple categories to avoid burden shifting [30]. This represents a consistent pattern found across the reviewed literature, meaning a redistribution of environmental burdens when moving from fossil-based to lower-impact or renewable ammonia production routes. The fact that such multidimensional behaviour indeed takes place is reflected in various articles, such as Chisalita et al. [55], Boero et al. [56], and Bicer et al. [51], where improvements in one category are often accompanied by trade-offs in others. Mohamed et al. underscore that these outcomes remain highly context-dependent, changing with the electricity mix, system boundaries, and process configurations. It therefore highlights the need for more harmonised and integrated LCA approaches that can be coupled with energy and techno-economic assessments, improving consistency and comparability across pathways while enabling a more comprehensive interpretation of sustainability [30]. From an economic perspective, the harmonised LCOA comparison shows that cost remains a key barrier for scaling low-carbon ammonia beyond conventional production, reflecting sensitivity to energy costs, CAPEX, capacity factor, and where CCS is applied, the availability and cost of CO_2 transport and storage [6], [9]

3.3 Limitations

Despite efforts toward the harmonisation of available data and assumptions, some methodological limitations are inherent in this comparative 3E analysis.

First, results are based on literature data that are heterogeneous in terms of system boundaries, geographical scope, and time frame, heterogeneity that cannot be completely removed. LCA indicators were gathered from studies adopting different boundary definitions: 15 cradle-to-gate, 1 well-to-site and 2 cradle-to-grave assessments, which inevitably affects comparability across impact categories and technologies. The environmental assessment is also limited to a selected spectrum of indicators that, although representative, cannot cover the full set of potential impacts in a life cycle perspective. Furthermore, representing the full range of LCA's impact indicators with sufficient statistical robustness, would have required the inclusion of a far larger number of studies than those collected.

Even though boundaries and key assumptions were aligned as much as possible, there are still several upstream processes such as electricity mix, feedstock origin, or CO_2 capture configuration, which could affect the relative performance of each route. Furthermore, this analysis is intended to be a snapshot in time that does not consider how learning effects, efficiency gains, and cost reductions may change environmental, consumption and economic outcomes.

Moreover, economic indicators, such as the LCOA, are still very sensitive to exogenous parameters such as fuel prices, carbon taxation and electricity tariffs, that may strongly vary depending on the market and policy context. Finally, the reduced sample size for some routes, reduces the statistical robustness of results. Ultimately, the 3E framework itself separates energy, environment, and economic dimensions, to a large extent, whereas in reality, all these aspects are strongly interlinked.

4 Infrastructure, logistics and safety

Ammonia relies on dedicated and integrated logistics infrastructure system that includes production plants, storage facilities, terminals and transport corridors, enabling distribution from producers to end-users. This infrastructure base is already widespread, but scaling low-carbon ammonia for new energy uses requires targeted expansion and adaptation of terminals, storage, and distribution networks [6], [11].

Since ammonia is hazardous, logistics design and operations must integrate safety requirements across transport, storage, and handling to manage health and environmental risks as volumes scale up [6], [9]

This chapter first reviews ammonia storage with emphasis on physical-based solutions, and then outlines ammonia transport by maritime shipping, road and rail, and pipeline, concluding with a brief comparison across transport modes.

Safety considerations are addressed throughout these sections, in relation to storage, handling, and transport operations, while the subsequent parts discuss the interface between storage and transport systems, summarise the regulatory framework, and review existing infrastructure and planned expansions with a regional focus on the United States, Europe, and Eastern Asia (Japan, South Korea and Singapore). These Asian jurisdictions are mentioned because ongoing initiatives explicitly focus on the creation of ammonia import/supply-chain bases and port-related energy logistics functions, highlighting their potential role as future hubs [89].

4.1. Ammonia storage

Storage plays a central role in the ammonia supply chain, because it decouples production from downstream logistics and end-use demand, enabling buffering across time and location. The storage options are commonly classified into physical-based and material-based approaches, as summarised in Figure 53.

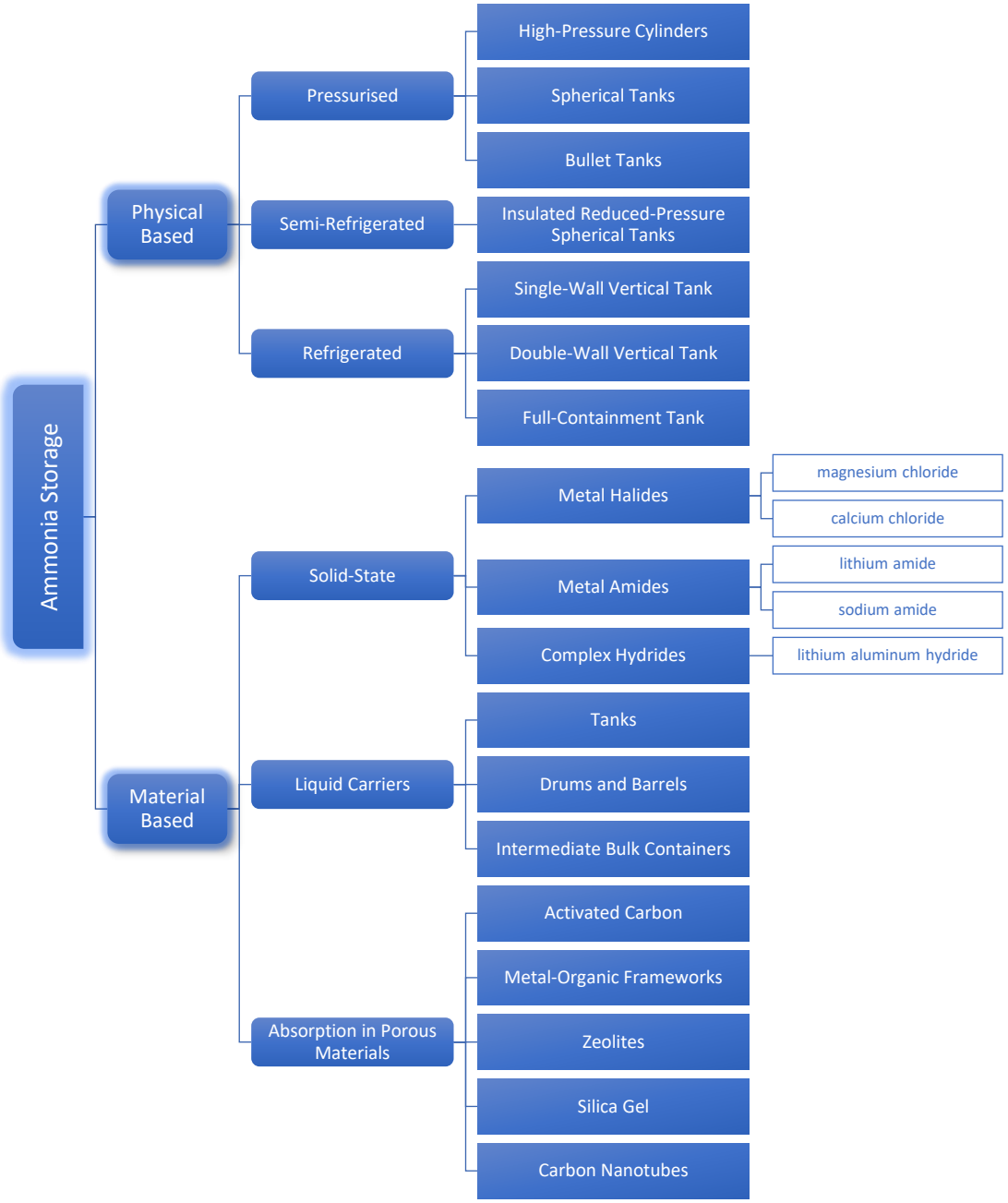

Figure 53 – Physical- and material-based ammonia storage options. Author elaboration from [3], [90].
Primary classification adapted from [90];
physical tank options and operating conditions cross-checked with [3].

Physical-based storage methods rely on liquid anhydrous ammonia and implement containment systems that achieve liquefaction through pressurisation, refrigeration, or a combination of the two.

Material-based storage options include solid-state systems (reversible ammonia uptake in solid compounds), liquid carriers (liquid phase different from pure anhydrous ammonia), and absorption/adsorption in porous materials, which are

presented in Figure 53 as alternative or emerging solutions. These approaches are generally discussed as routes to improve safety and operational flexibility by reducing the inventory of free liquid ammonia, but they can involve lower effective ammonia density and additional handling steps compared with anhydrous liquid storage, and they remain less mature for large-scale deployment.

The following section focuses on physical-based storage (pressurised, semi-refrigerated, refrigerated), because these solutions are described as the most technologically mature and widely adopted, while the remaining categories are included for completeness as emerging alternatives [3], [90].

4.1.1. Physical-based storage

Physical-based ammonia storage relies on established tank concepts that differ in operating philosophy (pressurised, semi-refrigerated, refrigerated), but they share a common requirement: the containment materials must be compatible with ammonia service over long lifetimes [6].

For carbon steels and some alloys, a key integrity concern frequently discussed in the literature is SCC, which is the formation and growth of cracks driven by tensile stress in combination with a specific corrosive environment, often initiating at surface defects or weld-affected regions and propagating over time.

In ammonia service, SCC is treated as a cross-cutting risk for steel-based equipment because susceptibility depends on the material condition and stress state as well as on service conditions, so it is considered when selecting materials and defining fabrication, inspection, and operational practices across physical storage concepts [6], [91].

Copper and copper alloys are not compatible with ammonia; therefore, components such as valves, fittings, and small hardware items are selected to explicitly avoid these materials. This requirement is particularly relevant for ancillary components where assemblies can unintentionally introduce non-compatible alloys even when the main tank shell is suitable [6].

Table 10 reports qualitative compatibility ratings for a broad set of materials with ammonia, providing a general reference for materials' choice.

Table 10 – Materials compatible with ammonia [6].

Material	Rating	Material	Rating	Material	Rating
ABS Plastic	D	Carbon graphite	A	Polycarbonate	D
Acetal (Delrin)	D	Carbon steel	B	PEEK	A
Aluminium	A	Carpenter 20	A	Polypropylene	A
Brass	D	Cast iron	A	Polyurethane	D
Bronze	D	Ceramic Al_2O_3	N/A	PPS (Ryton)	A
Buna N (Nitrile)	B	Ceramic magnet	N/A	PTFE	A
Copper	D	ChemRaz (FFKM)	B	PVC	A
CPVC	A	EPDM	A	PVDF (Kynar)	A
Epoxy	A	Hastelloy-C	B	Silicone	C
Fluorocarbon (FKM)	D	Hypalon	D	Stainless Steel 304	A
HDPE/LDPE	B	Hytrel	D	Stainless Steel 316	A
Natural rubber	D	Kalrez	A	Titanium	C
Neoprene	A	Kel-F	A	Tygon	A
NORYL	B	Nylon	A	Viton	D

A = excellent;
B = good (minor effect, slight corrosion);
C = fair (moderate effect, not recommended for continuous use);
D = severe (not recommended); N/A = information not available.

Table 11 reports the typical operating conditions and indicative design implications of the three physical-based storage concepts.

Table 11 – Typical operating conditions and scale indicators for ammonia storage [3].

Storage method	Typical pressure [bar]	Design Temperature [°C]	Steel cost [tNH3/t_{steel}]	Capacity [tNH3]	Refrigeration compressor
Pressurised	16-18	20-25	2.8-6.5	<2000	None
Semi-Refrigerated	3-5	0	10	450-2500	Single stage
Refrigerated	1.1-1.2	- 33	41-45	4500-50000	Two stages

From a design perspective, it's possible to note that:

- Pressurised storage is characterised by ambient-temperature operation without refrigeration, but it relies on thick-walled containment and therefore tends to be the most steel-intensive option. This typically makes it more attractive for small to medium installations, especially when storage is closely integrated with road and rail distribution;
- Semi-refrigerated storage represents a transitional approach: it reduces vapour pressure through partial cooling while maintaining relatively moderate refrigeration complexity. It is often selected where capacities exceed typical pressurised storage needs, but full refrigeration is not justified or where operators prioritise a balance between infrastructure requirements and operational flexibility;
- Refrigerated storage operates at low temperature and near-atmospheric pressure, enabling high-capacity installations with comparatively efficient use of structural material. This option is therefore preferred for large storage sites and terminals, although it requires continuous refrigeration and associated utilities, which increases operating complexity.

Table 12 and Figure 54 provide complementary detail on physical tank configurations and containment philosophies, with the table focusing on typical materials, while the figure illustrates representative refrigerated tank layouts and secondary containment concepts.

Table 12 – Typical tank types and associated construction materials for ammonia storage.

Storage Type	Materials Used	Ref.
Pressurised Vessels (bullet tanks)	Carbon steel (thick-wall)	[92]
Semi-refrigerated Tanks (spherical or cylindrical)	Carbon steel suitable for low-temperature service or austenitic stainless steel with external insulation layer	[92]
Refrigerated Single-Wall Tanks	Carbon steel suitable for low-temperature service with external insulation layer	[6], [9]
Refrigerated Double-Wall Tanks	Carbon steel inner tank + outer steel wall and insulation layer/gap	[6], [9]
Refrigerated Full Containment Tanks	Inner steel tank + outer reinforced structure (typically steel+concrete) and insulated layer/gap	[6], [9]

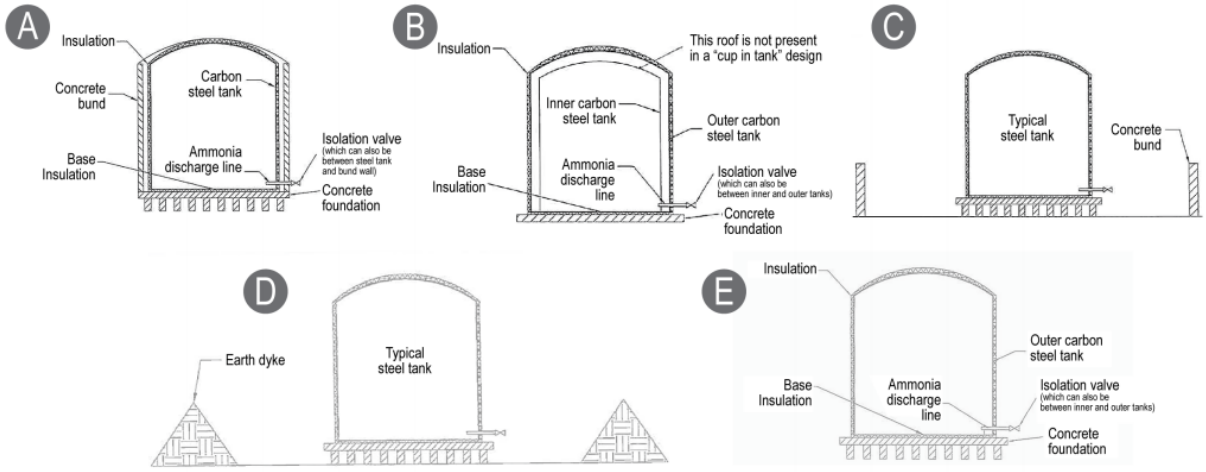

Figure 54 - Schematic cross-sections of refrigerated ammonia tank configurations (A-E) [6].

These configurations are interpreted as a progression in containment performance from E (lowest) to A (highest), while the figure primarily highlights typical tank construction features and does not explicitly depict all site-level mitigation measures. It can be noted that:

- Single-wall tanks (C, D, E) rely on external insulation; C and D also show a bund or earth dyke, whereas E does not depict a dedicated secondary containment structure; however, it may be addressed through site-level design outside the tank cross-section;
- Double-wall tanks (B) include an inner and outer steel shell with an insulated layer or gap, providing enhanced containment relative to single-wall designs, typically entailing higher upfront capital cost;
- Full-containment tanks (A) add an outer reinforced structure around the inner steel tank and are designed to retain the full inventory even in the event of inner tank failure, making them the preferred solution where the highest level of containment performance is required.

Another key difference between pressurised and refrigerated storage is how heat ingress and vapour generation are managed, with implications for safety, energy use, and emissions control:

- In pressurised tanks, the system is designed to tolerate pressure increase within operating margins, and pressure relief devices are used as a protection measure for abnormal scenarios rather than as routine boil-off handling [93];
- In refrigerated tanks, a small continuous boil-off is expected due to heat transfer through the tank walls and is handled via a closed refrigeration loop, where the

vapour is cooled and returned to the tank as liquid. Typical boil-off rates (fraction of inventory that vapourises per day) reported for large, refrigerated tanks are on the order of 0.03% to 0.10% per day, which provides a practical benchmark for continuous thermal management performance [90], [91].

In addition to the management strategies described above, safety systems are typically adopted to further reduce operational and environmental risks. Examples include:

- Leak detection and monitoring systems, which provide early warning through fixed detectors and continuous measurements to support timely isolation and response actions;
- Ventilation systems, which are used to dilute and remove ammonia vapours in enclosed or semi-enclosed areas to reduce exposure and accumulation;
- Water curtains, which are used as a mitigation measure to absorb and knock down ammonia vapours and to help control the dispersion of accidental releases [6], [94].

Table 13 compares pressurised and refrigerated ammonia storage, summarising indicative capital and operating expenditures, specific operational energy requirements and typical lifetime based on literature and industry guidelines. These values should be considered as order of magnitude benchmarks rather than exact project costs; however, they provide a useful basis for comparing the two main options. Specific data for semi-refrigerated tanks are not explicitly reported, so its cost positioning is discussed qualitatively based on its intermediate operative conditions.

Table 13 – Indicative CAPEX, OPEX, energy consumption and lifetime for pressurised and refrigerated storage based on [95], [96].

Storage type	CAPEX [USD/kgNH3]	OPEX [%CAPEX per year]	Energy use in operation [KWh/kgNH3 per year]	Typical lifetime [years]
Pressurised	3	Minimal (not quantified)	energy only for compression/pumping during transfers (not quantified)	26–52
Refrigerated	0.56–1.06	3%	0.038 (only for refrigeration)	20–40 (*)

(*) oldest reported 45 years

These data indicate that:

- Pressurised storage minimises energy use during steady operation, so OPEX is mainly driven by inspection, maintenance, and compliance rather than continuous power demand;
- Semi-refrigerated storage represents an intermediate option: it reduces vapour pressure through partial cooling and typically requires less extensive continuous refrigeration infrastructure than fully refrigerated storage; therefore, its expected CAPEX, OPEX and operational energy intensity to fall between pressurised and refrigerated solutions;
- Refrigerated storage benefits from large-tank design and construction practices, which typically improve the cost effectiveness of installed capacity; however, it requires continuous utilities for refrigeration and therefore entails a higher operational energy and OPEX profile.

Accordingly, refrigerated tanks are typically adopted for large import/export terminals and production hubs, whereas pressurised tanks are suitable for smaller decentralised sites, and semi-refrigerated tanks are applied where intermediate capacity and reduced refrigeration requirements provide a practical compromise [3].

4.2. Ammonia transport

Transport modes rely on the storage concepts introduced in the previous section, because the same containment and handling solutions are adopted and adapted for mobility; in practice, transportation uses storage systems that are scaled to the required capacity and configured for the specific transport application [96].

Ammonia is routinely transported by ship, barge, road, rail and pipeline, the choice of one mode or another depends on the supply context and distibution needs [9].

4.2.1. Maritime

Maritime transport is vital for the global supply chain of ammonia, acting as a strategic link between remote production centres and distant consuming regions. Ammonia is already shipped routinely in bulk, with approximately 20 Mt moved by sea in 2024; however, its future role as a carbon-free energy vector and hydrogen carrier is expected to position maritime transport as a fundamental pillar of the energy transition, as nations seek to move low-carbon fuels at large scale [97], [98].

In operational terms, seaborne ammonia trade develops along corridors connecting export hubs and import terminals. Therefore, the first-order driver is route length, which affects voyage duration and the “logistics cycle” of a vessel.

Table 14 presents scenario-based evidence for an 84000 m^3 ammonia carrier, illustrating the magnitude of geographic variability on Asia-bound supply.

Table 14 - Example of route distances for a 84000 m^3 ammonia carrier [98].

Origin	Destination	Indicative distance [km]
USA (Port of Houston)	Korea (Port of Ulsan)	26514
Saudi Arabia (Port of Dammam)		12043
Australia (Port Gladstone)		8510

A comparable effect is observed on Europe-bound corridors, where India-Europe transport cost for shipments from Paradip to the KrK import terminal in Croatia differ markedly between Suez Canal and Cape of Good Hope routing. In this case, the same origin-destination pair can shift from 43 days (Suez) to 85 days (Cape), and this increase in voyage duration is reflected in higher transport costs: rising from about 59-73 USD/Mt for a Large Gas Carrier (LGC) via Suez to about 96-126 USD/Mt via Cape, while for Medium Gas Carrier (MGC) the same change is from about 91-108 USD/Mt to about 154-190 USD/Mt [99]. Accordingly, vessel classes can be interpreted as a practical response to trade patterns and port/terminal constraints. Table 15 summarises the major carrier types, containment systems and typical capacities.

Table 15 - Carrier types, containment systems and typical cargo volume and mass. Author elaboration based on [97], [100].

Ship Size	Tanks Type Containment system	Cargo Volume [m^3]	Cargo Mass [t_{NH_3}/voyage]
Small Gas Carriers (SGC)	Fully Pressurised Cylindrical (on the deck)	1000 – 5000	600 – 3000
Medium Gas Carriers (MGC)	Semi-Refrigerated Spherical/Cylindrical insulated (in the haul)	5000 – 30000	3000 – 20000
Large and Very Large Gas Carriers (LGC/VLGC)	Fully Refrigerated Prismatic insulated (in the haul)	30000 – 90000	20000 – 60000

It can be noted that:

- SGCs adopt pressurised storage systems with modest capacities, hence they are typically used for coastal and short haul routes, making them suitable for ports with limited infrastructure. In addition to ocean-going carriers, pressurised barges can be considered a subset of maritime/short-sea and river-sea ammonia transport, typically supporting coastal distribution, inland waterways and last-mile delivery to smaller terminals [99];
- MGCs use semi-refrigerated storages hence can load at both pressurised or refrigerated terminals, making them suitable for regional trade, balancing cargo capacity and port access, while providing operational versatility;
- LGCs and VLGCs use refrigerated atmospheric storages, loading tens of thousands of t per voyage and are optimised for intercontinental routes.

From a regulatory and technical standpoint, since both Liquefied Petroleum Gas (LPG) and anhydrous ammonia are liquefied gases covered by the same International Maritime Organisation (IMO) International Gas Carriers (IGC) Code and require similar storage conditions, ammonia can be carried on LPG carriers that only require compatible materials and enhanced crew-protection systems; consequently, many modern gas carriers are built or upgraded to be LPG/ammonia capable and can switch between these cargoes with minor design modifications [97], [101], [102]. The size of the ammonia-capable fleet and the number of vessels actively trading ammonia are discussed in Section 4.5.

Despite ammonia's long history as a traded chemical, its transport poses safety and handling challenges that make the shipping infrastructure especially critical. In addition to the preventive and safety measures outlined for storage in Section 4.2.1, gas carriers transporting ammonia as cargo must also incorporate ship-specific features such as:

- Gas-tight segregation between cargo and non-cargo spaces;
- Accommodation and machinery air intakes located away from vent risers and fitted with closure devices;
- Fixed dry-powder systems for fire and vapour control;
- Dedicated personal protective equipment (PPE);
- Deck showers and eye-wash stations [101], [103].

Beyond technical suitability and safety, investment considerations (ship CAPEX) matter, because scaling ammonia trade requires additional dedicated tonnage over time. A techno-economic assessment for an 84000 m^3 class ammonia carrier provides an indicative reference point for newbuilding costs and the incremental impact of

alternative propulsion concepts: 71.0 MUSD for a conventional-fuel propulsor, increasing to 80.7 MUSD for an ammonia-fuelled propulsor and 80.4 MUSD for an LNG-fuelled [98].

In parallel to its role as cargo, ammonia is increasingly being considered as a marine fuel option to support decarbonisation pathways, which implies integrating ammonia into the maritime fuel supply chain through dedicated bunkering infrastructure [11]. At a high level, bunkering can be organised either as berth-based ship-to-shore transfer, or via a bunker supply vessel enabling controlled ship-to-ship operations [99]. Compared with conventional marine fuels, ammonia bunkering is more demanding because leak or vapour-release consequences are more severe and transfer operations require tighter control of containment integrity and emergency shutdown behaviour; for the detailed description of the transfer-interface see Section 4.3 [103].

4.2.2. Road and Rail

Road and rail transport provide the main inland connection between import/export hubs, regional storage sites, and geographically dispersed end users when dedicated pipelines are unavailable or not yet expanded. Rail typically serves high-throughput, medium-to-long inland corridors, while road transport covers shorter or "last mile" delivery, enabling flexible distribution to smaller or more dispersed demand centres [90].

Ammonia is commonly moved on land as a pressurised liquid, so both modes rely on certified pressurised vessels as the primary containment system. Rail freight uses specialised chemical rail tank cars with individual capacities up to 110 t, and trains can move large batches per trip (often tens to over one hundred cars, depending on the consist and route constraints). Road transport relies on heavy goods vehicles equipped with pressurised tank units, with typical payloads around 36 t per trip, which makes trucking well-suited to shorter, distributed deliveries but comparatively less efficient for large volumes over long distances [3], [90], [96].

Regarding costs:

- CAPEX: both modes require the mobile containment asset and compatible loading/unloading interfaces with safety systems at terminals. For rail transport, the Rail Tank Car (RTC) is a regulated pressure vessel system whose design, certification, fittings arrangement, and testing regime follow rail dangerous-goods rules. For road transport, CAPEX is concentrated in the pressurised tank equipment and the interfaces needed at depots/consumers to connect, transfer, and isolate ammonia safely; compared with rail, road CAPEX

is usually deployed in smaller increments (more vehicles, smaller units), supporting flexibility and phased scale-up [90];

- OPEX: recurring drivers include trained labour, preventive maintenance, inspections and periodic testing, and energy/fuel consumption. Techno-economic parameters set for inland distribution include staff wages, fuel prices, and maintenance costs per km for both modes, with rail typically showing lower fuel and maintenance intensity per t·km at high utilisation. Since ammonia logistics often involve empty returns, scheduling and asset utilisation strongly influence effective OPEX for both road fleets and rail consists [90], [96].

Rail tank cars and tank trucks are engineered with safety as a primary constraint, using high-strength materials to withstand mechanical stresses and transport loads, while maintaining ammonia in a stable liquid form during transit. Some of the safety features include:

- Reinforced structures and crash-resistance measures, to reduce the probability of release during accidents;
- Thermal protection (including heat-shield arrangements) to limit heat input and reduce undesired vapourisation and pressure rise;
- Pressure relief devices to prevent over-pressurisation that may lead to ruptures or leakage [104], [105].

Figure 55 shows a typical ammonia RTC, including the heat-shield configuration and the placement of key external equipment.

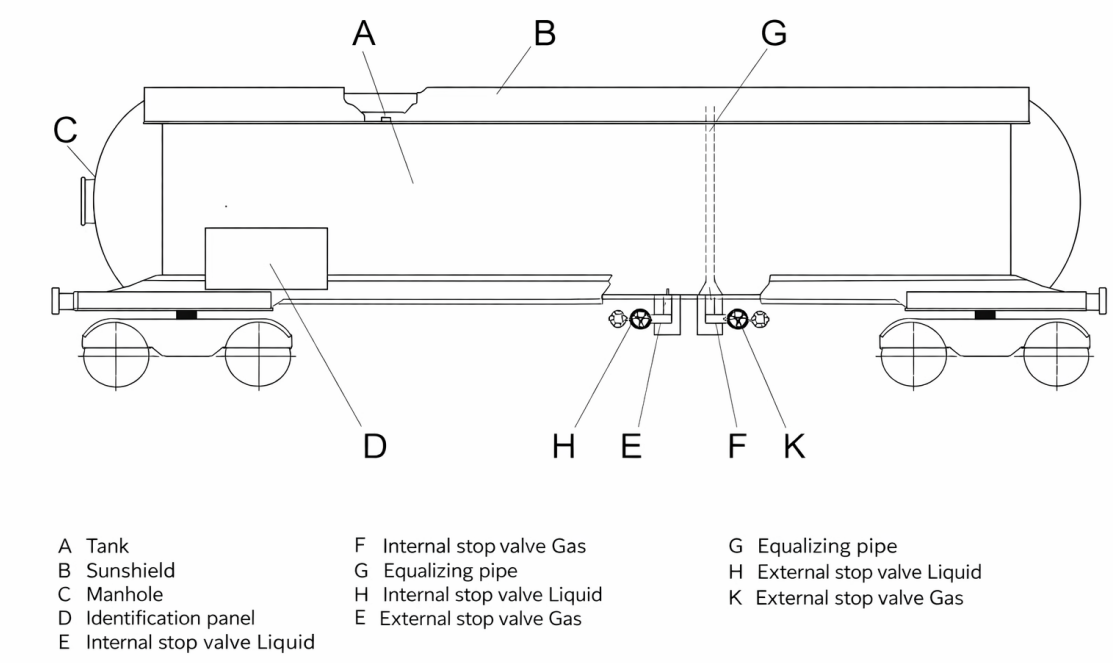

Figure 55 - Ammonia RTC arrangement [105].

Operational safety also depends on compliance with hazardous-materials frameworks, correct marking/identification, and trained personnel executing standardised procedures during loading/unloading, including emergency shutdown capabilities and mitigation measures, such as water screens to suppress ammonia clouds [104], [105].

Overall, these two transport modes remain complementary: rail supports efficient inland movement of large ammonia quantities where rail infrastructure and terminals enable batch operations, while road provides decentralised distribution and last-mile deliveries with smaller, modular assets. As low-carbon ammonia scales beyond traditional markets, this combination continues to enable practical inland logistics, provided that compliant equipment and engineered transfer facilities are matched by robust operating procedures and regulatory adherence [90], [104], [105].

4.2.3. Pipeline

Ammonia pipelines represent a midstream option for moving large volumes between production facilities, import hubs, storage terminals and inland industrial users, complementing maritime shipping for long-distance trade and road/rail for shorter or more flexible distribution.

Today, pipeline networks are geographically concentrated, with the largest share of existing infrastructure located in a limited number of regions; this existing base, besides providing an important foundation for future expansions, suggests that the main barriers to growth are more about permitting, financing, siting and building new corridors that can safely handle larger volumes, rather than technical novelty [6]. The current network extent and geographical distribution are discussed in Section 4.5.

The interest in large-scale pipelines is rising in Europe, as it aims to position itself as one of the main hydrogens and clean-fuels hubs. Therefore, ammonia pipelines become an urgent additional transport mode to connect ports with inland terminals and consumers [106].

In this context, pipeline economics are typically characterised by high upfront CAPEX (pipe material and installation, right-of-way, civil works, stations) and comparatively lower routine O&M once the corridor is in operation. As an indicative 2019 reference case, rural pipeline CAPEX is reported around 0.857 MUSD/km, increasing to 1.469 MUSD/km in urban sections, while general O&M is reported at about 500 USD/km·y. Pumping needs are represented via booster stations: one example assumes 128 km spacing, with roughly 1.22 MUSD of booster equipment CAPEX plus roughly 1 MUSD per station for construction/installation, and 0.408 MUSD/y in operating cost per station [96].

For new, large-scale European corridors, the Institute for Sustainable Process Technology (ISPT) reports that safety/compliance-driven design choices can materially increase investment levels. The analysis is presented as a study case (not an announced project) aligned with the Delta Rhine Corridor concept, assuming 550 km and approximately 7 Mt/y of clean ammonia transport from the Port of Rotterdam to Karlsruhe. Under these assumptions, total CAPEX is estimated at 1.6 B€ for a basic design and 2.1 B€ for a "safe and compliant" design; total annual costs (OPEX plus annualised capital costs) are reported at 240 versus 310 M€/y [106].

Ammonia pipelines typically transport it either cold liquid close to –33°C or as warm/ambient liquid. The choice between cold and warm operation generally depends on the source and storage/handling destination conditions, since pipeline transport is integrated with terminals and storage systems that may be refrigerated or pressurised [106], [107].

A recurring operational issue for cold service or uninsulated lines is ice formation, which may increase loads on pipe supports, freeze valves or other equipment, creating risks in both routine and emergency conditions. Where sub-zero operation is unavoidable, vapour-tight insulation or localised heating is highly recommended. These operational aspects imply the need to manage both thermal and pressure effects to maintain liquid phase, avoiding flashing and two-phase flow [106], [107].

Despite being one of the safest distribution modes, with a safety record 2 times better than other pipelines and 7-8 times better than other forms of bulk transportation, this performance depends ultimately on robust design choices together with layered safety measures [6].

From a design perspective:

- The pipe diameters are typically at least 75 mm, while large long-distance trunk lines are reported up to about 350 mm; in practice, major high-throughput branches are commonly in the 200-250 mm range;
- Wall thickness is typically below 20 mm (about 15–19 mm depending on diameter and design pressure), with 15 mm highlighted as a minimum regulated thickness associated with a marked reduction in external-damage failure frequency in Europe. For locally sensitive sections (canal crossings), an EU case reports increased wall thickness at that location rather than a uniform increase. In higher-consequence segments (crossings and corridors near populated areas), this is typically combined with mechanical protection and monitoring measures to reduce third-party damage risk and limit release consequences;

- The material used is typically carbon steel, however, there's a trend toward stainless steel for specific cases, such as when replacing sections or building short/small-diameter lines, due to improved corrosion resistance and lower long-term maintenance burden [106], [107].

From a safety standpoint, most of the pipelines must be built and fit with the following requirements:

- Route selection and risk-based corridor planning, minimising exposure to populated areas and aligning with national risk/permitting frameworks as the first preventive layer for toxic-related hazards;
- Underground-routing for most off-site ammonia pipelines, with a burial depth between 1.5 and 2 m, reducing third-party interference risk;
- External coating layers and impressed current cathodic protection, to prevent long-distance pipelines from external corrosion;
- Segmentation with isolation valves (ideally remotely operable) and risk-based section length, to limit inventory release;
- Multi-layer leak detection (leak ammonia sensors, mass balance, pressure-drop monitoring, acoustic and soil temperature approaches) improving the detection of different leak-sizes and scenarios;
- Thermal relief protection is required for blocked-in sections, since trapped liquid can expand when heated, creating overpressure and secondary leak risks;
- Inspection, integrity management and emergency planning provide the final safety layer, with routine checks of stations/valves and release-response plans where large inventories and national requirements apply [106], [107].

Figure 56 introduces a schematic cross-section of a buried ammonia pipeline trench, summarising typical integrity and safety measures.

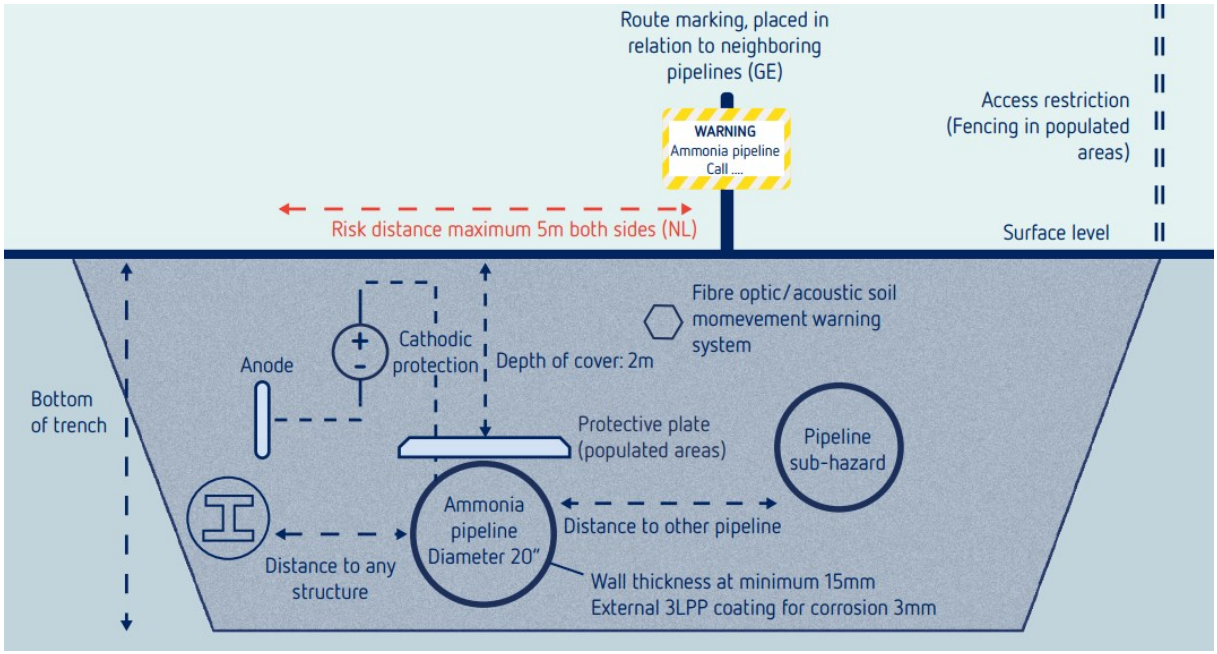

Figure 56 - Schematic cross-section of a buried ammonia pipeline trench and indicative risk-reduction measures [106].

A central question, yet under-investigated, is whether new corridors should rely on dedicated pipelines or retrofit existing assets built for other products. Historically, ammonia lines benefited from joint construction with LPG and refined-products infrastructure, reducing rights-of-way and construction costs, suggesting that repurposing may not require special metallurgy provided that detailed survey, testing and recommissioning are carried out. For large-scale corridors serving new energy uses, the uncertainty may favour investment in dedicated lines designed to meet stringent risk criteria, especially in densely populated areas [6], [106]. In practice, a hybrid pathway appears most credible: selective retrofitting where the conditions are favourable, combined with new dedicate lines for strategic high-volume routes, balancing cost and permitting advantages with modern safety requirements.

4.2.4. Comparison between transport modes

To consolidate the main qualitative differences discussed in the previous Sections (4.2.1, 4.2.2, 4.2.3). Table 16 compares ammonia transport modes in terms of representative shipment distance, payload scale and indicative transport service costs.

Table 16 – Quantitative comparison of ammonia transport modes. All cost values reported refer to indicative specific transport service costs (tariffs/operating transport costs), expressed per unit of mass (t) and distance (km).

Mode	Avg. distance [km]	Typical payload / capacity	Specific service cost [USD/t·km]	Ref.
Maritime – Gas carriers (tankers)	1770	20000–40000 t per ship (typical)	0.006–0.065 (*)	[6], [96]
Maritime – Barges (inland waterways)	(**)	500–3000 t per barge	—	[6], [92]
Rail	1873	3500–16500 t per train (***)	0.03	[6], [96]
Road	188	10–30 t per truck	0.21	[6], [96]
Pipeline	455	up to 3 Mt/y	0.04–0.05	[6], [90]

(*) : derived from route-based examples [96] and divided by the average distance per mode reported in [6]

(**) : included in "marine vessel"

(***) : computed as (70–110 t per car) x (50–150 cars/train)

It can be noted that:

- The average distance covered by maritime gas carriers (1770 km) is consistent with their role for long-range transport, while scale effects are captured by typical cargoes between 20-40 kt, positioning this mode as the most suitable for international bulk-trade. Offshore transport costs on some route-based examples are reported in the range of 11.4-115.8 USD/t depending on destination and vessel type (MGC/LGC), under the stated assumptions; this variability is influenced by charter rates, distance travelled, fuel consumption and port charges/tariffs [96]. Consistently, IRENA describes ship transport as potentially adding up to 45-100 USD/t to local production costs for import projects, which falls in the same range stated above [9];

- Barges are framed as a sub-set of marine logistics, but with smaller cargo units (0.5-3 kt per barge). This supports their typical role as a regional feeder mode in rivers, estuary and short coastal legs. Costs are often highly route- and terminal-dependent and therefore not reported as a single representative value or range across sources; however, in qualitative terms, inland-waterway barges are described as cost-effective option for navigable waterways [90];
- The long average distance (1873 km) reflects rail's positioning as a long-haul inland option when infrastructure exists, while the reported payload logic (tank car up to 110 t with multi-car convoys reaching several kt per train) explains why rail can move large inland volumes. The indicative cost (0.03 USD/t·km) aligns with sources that explicitly describe rail as cost-effective for bulk inland transport but constrained to corridors with rail access, which is typically provided in many medium/large ports [96];
- The short average distance for road transport (188 km) matches the typical last-mile and regional distribution role, consistent with the smaller payload per unit (10-30 t). The higher unit cost (0.21 USD/t·km) is coherent with the lack of economies of scale compared to rail and pipelines, while providing more flexibility. Moreover, an economic upper bound distance of 770 km is explicitly reported in the literature as a practical ceiling beyond which trucking becomes economically prohibitive for ammonia logistics [96];
- The average pipeline's transport distance (455 km) should be interpreted as infrastructure-conditioned: only a small number of dedicated long-distance pipelines exist, while many networks are short and localised. Despite that, pipeline transport can achieve competitive tariffs (0.04-0.05 USD/t·km), making it an attractive option for dedicated corridors that require a constant throughput of ammonia [6], [96].

In conclusion, this modal split is consistent with the view that the most suitable transport option depends on trade-offs regarding distances, volumes, infrastructure availability and costs [90].

4.3. Interface between storage and transport systems

In ammonia logistics, storage and transport play complementary roles: storage nodes (terminals, tanks, tank farms) provide capacity and buffering over time, while transport units (ships, trucks/railcars, pipelines) provide mobility and flow over distance. In practice, storage installations are designed to hold comparatively large inventories over longer time horizons: typical import tanks may be filled and emptied every 1-2 weeks, while transport assets carry smaller inventories per unit and are constrained by transfer rates and route/distance [6], [91].

The storage-transport interface is therefore concentrated at localised transfer boundaries, where ammonia is moved from one containment system to another, such as ship/shore manifolds, truck/rail loading bays, or pipeline terminal tie-ins [106], [108]. These boundaries typically concentrate the most stringent operational and safety requirements because they combine temporary connections/disconnections, transfer transients, and the need to manage pressure/temperature behaviour and vapour displacement during operations.

Figure 57 illustrates a representative ship-shore transfer point, including the loading arm, Emergency Release System (ERS), and typical isolation/Emergency Shutdown (ESD) systems at the transfer boundary [108].

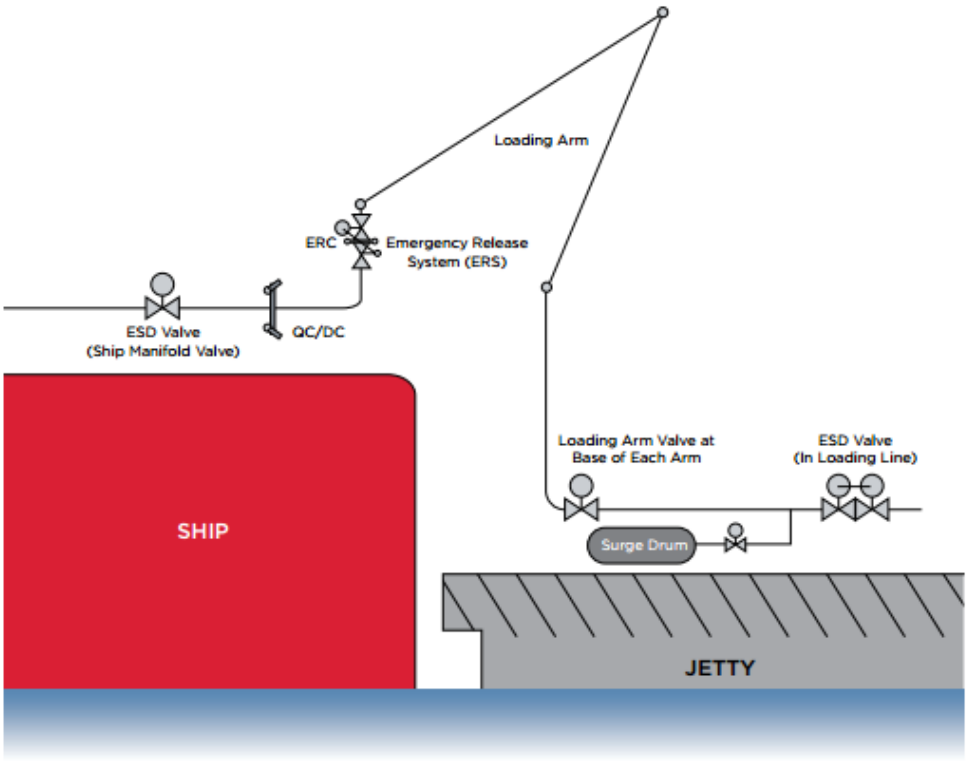

Figure 57 - Ship-shore transfer layout for ammonia bunkering highlighting the hardware, ERS and ESD systems [108].

A practical way to frame the Balance of Plant (BoP) at the interface is that transfer operations commonly require:

- Fluid movement and pressure management, provided by suitable fluid-handling machinery and control, including pumps, compressors or equivalent pressure-control arrangements depending on pressure levels and operating philosophy;
- Conditioning, when the receiving system requires a different pressure/temperature regime, which may involve heating/cooling, controlled depressurisation and vapour management [106], [108].

Since ammonia can be transferred under different pressure-temperature regimes (commonly pressurised liquid at ambient temperature or fully/semi refrigerated liquid close to atmospheric pressure), interface requirements vary with the upstream/downstream conditions, which are summarised in Table 17.

Table 17 - Interface focus according to upstream and downstream storage regimes. Author elaboration [91], [108].

Upstream regime	Downstream regime	Interface focus
Pressurised	Pressurised	▪ Maintain controlled transfer conditions and isolation; ▪ Vapour return is typically not required.
Fully/Semi-Refrigerated	Fully/Semi-Refrigerated	▪ Strict temperature control at the boundary; ▪ Vapour return line is commonly provided.
Fully/Semi-Refrigerated	Pressurised	▪ Conditioning to achieve required delivery pressure/temperature; ▪ Explicit vapour management at the boundary.
Pressurised	Fully/Semi-Refrigerated	

Overall, interface complexity increases when heat ingress and/or regime transitions make vapour generation more likely, requiring tighter thermal control, vapour routing and conditioning at the boundary.

Transfer points must also explicitly account for transients: even with nominal single-phase operation, short sections can retain liquid/vapour pockets and experience flashing or two-phase formation during cooldown/warm-up, start/stop, and line handling; therefore, residual inventory in transfer lines is a practical design assumption that the interface must manage safely before, during and after transfer.

Because filling a closed receiver displaces vapour and affects pressure, the interface often requires both a liquid transfer path and a vapour/vent (or vapour-return) path, supported by monitoring and interlocks to maintain safe pressure behaviour and prevent overfill/unsafe conditions [108].

Ultimately, interface hardware can be described as a transfer package combining liquid transfer equipment and vapour/vent connections, complemented by:

- Isolation and emergency shutdown functions;
- Provisions for inerting/purging and safe line conditioning;
- Breakaway/emergency release features where relevant;
- Coordinated shutdown and communication (especially for ship-shore transfer) [108]–[110].

Table 18 summarises typical operational triggers and the corresponding minimum interface functions expected at transfer boundaries.

Table 18 - Transfer-condition triggers and required interface functions [108], [110].

Condition trigger	Interface function
Closed receiver being filled	Liquid path + gas-phase/vent path + monitoring of filling
Transient with potential liquid/vapour remaining in transfer lines	Drain + inert gas purge connection(s) for line conditioning
Ship/shore cargo transfer	Coordinated shutdown logic to stop transfer equipment and isolate valves

Regarding pipelines, the storage-transport interface is concentrated at terminal tie-ins (pipeline entry and exit), where ammonia is injected into or withdrawn from the line and the terminal manages the transition between pipeline operating conditions and downstream storage/distribution requirements (Figure 58).

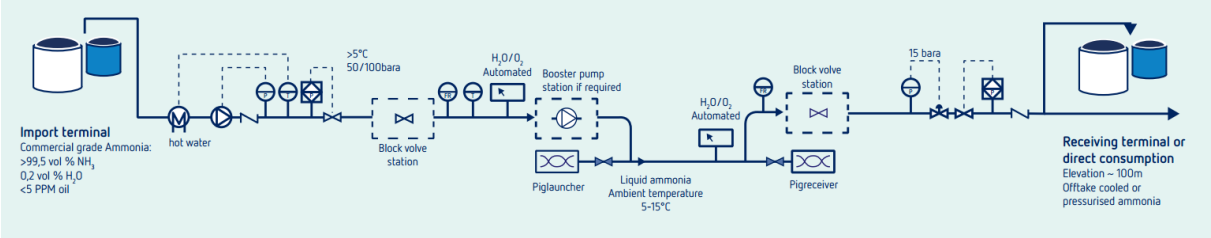

Figure 58 - Schematic overview of an ammonia pipeline including conditioning, isolation valve stations and optional boosting [106].

A key requirement for ammonia pipelines is maintaining single-phase liquid flow and avoiding two-phase conditions. To support this, refrigerated ammonia may require entry conditioning (heating from −33°C to at least 5°C, commonly up to about 15°C) prior to injection, while receiving terminals may require re-refrigeration if storage is needed [106]. Table 19 summarises the main pipeline interface locations, their focus, and the typical elements required close to terminal tie-ins.

Table 19 - Main pipeline interface locations and typical elements [106].

Interface location	Interface focus	Typical elements
Terminal tie-in (pipeline entry)	Entry conditioning to remain within the single-phase operating window	Heating/Conditioning step
Terminal tie-in (pipeline exit)	Controlled transition from pipeline conditions to downstream requirements	Re-refrigeration for storage or direct transfer to users
Near-terminal isolation points / tie-in piping	Isolation and overpressure protection of bounded sections to limit release and prevent blocked-in overpressure	Remotely operable isolation valves and thermal relief for blocked-in liquid sections

Close to terminals, interface design also includes segmentation and isolation to limit release and protect bounded sections, with remotely actuated isolation ESD valves and thermal relief to protect blocked-in liquid sections against pressure build-up from heat ingress and thermal expansion (Figure 59).

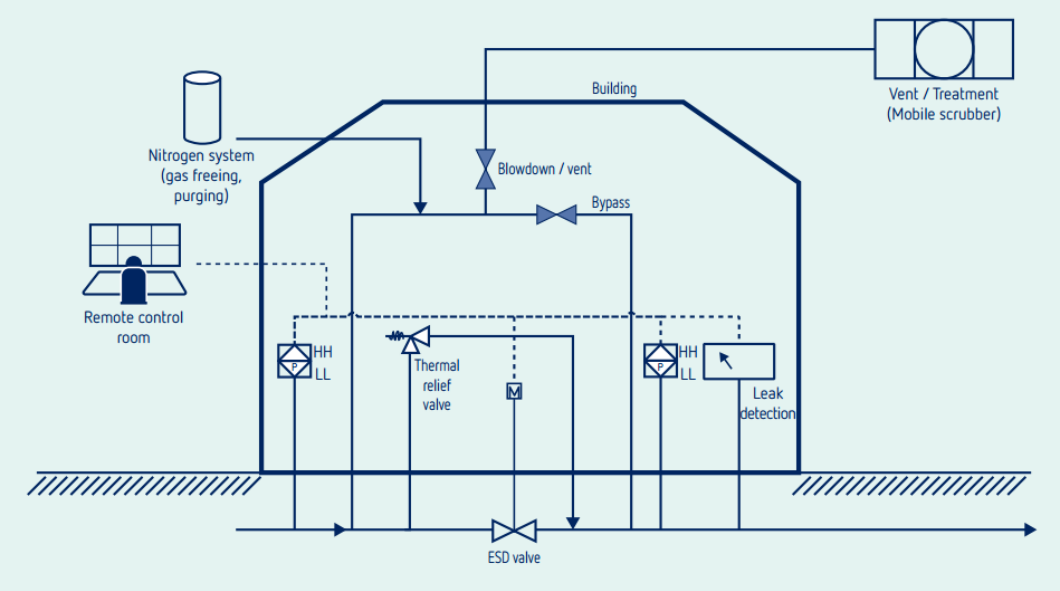

Figure 59 - Station layout highlighting operational and safety provisions: ESD isolation, nitrogen purging, controlled vent/treatment, leak detection and remote control [106].

4.4. Regulations

This section summarises the main regulatory and standardisation frameworks that are typically relevant for the compliance perimeter of ammonia logistics infrastructure.

It focuses on the main compliance interfaces such as maritime operations, inland transport, loading/unloading and transfer activities, major accidents and site safety duties, pressure equipment conformity and environmental controls, across the IMO domain as well as EU, USA, Japan, Republic of Korea, Singapore.

At the international level:

A. Maritime compliance is framed by IMO instruments that distinguish between bulk carriage of liquefied gases, governed by the International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk (IGC Code), and packaged dangerous goods, governed by the International Maritime Dangerous Goods Code (IMDG Code):
   i. Bulk carriage of liquefied gases: the IGC Code guides ship-side design and operational requirements [111];
   ii. Packaged dangerous goods: the IMDG Code sets obligations for carriage of dangerous goods in packaged form [112].
B. Marine emergency governance for hazardous and noxious substances is complemented by the Protocol on Preparedness, Response and Co-operation to Pollution Incidents by Hazardous and Noxious Substances (OPRC-HNS Protocol), which sets expectations for preparedness, response arrangements and international cooperation for HNS pollution incidents [113].

Table 20 summarises the IMO instruments discussed above.

Table 20 - Overview of key IMO instruments relevant to ammonia and other hazardous cargoes, summarising scope and typical applications.

Anchor instrument	What it governs	Typical application	Ref.
IGC Code	Bulk liquified-gas carriage baseline relevant to ship-side design and construction standards	Gas carriers (bulk liquefied gas)	[111]
IMDG Code	Mandatory requirements for carriage of packaged dangerous goods	Carriage of packaged dangerous goods	[112]
OPRC-HNS Protocol	Preparedness/response cooperation framework for HNS pollution incidents	HNS pollution incident preparedness/response arrangements (national/international)	[113]

In the European Union (EU):

- Inland movements are legally anchored by Directive 2008/68/EC, which applies to road, rail, and inland waterway transport and explicitly covers loading/unloading and transfer activities [114];
- For fixed sites with large inventories, Seveso III provides the fundamental major-accident prevention and consequence-limitation framework, including operator duties for internal emergency planning that typically define the regulatory envelope of sizeable logistic facilities [115];
- Conformity of pressure-containing equipment placed in the EU market is governed by the Pressure Equipment Directive (PED), making conformity assessment and associated documentation a key requirement for ammonia infrastructure components [116];
- Environmental compliance for installation within scope is framed by the Industrial Emission Directive (IED), which supports integrated permitting logic and conditions operational obligations related to emissions and environmental performance [117];
- Hazard communication that underpins safe handling and downstream controls is anchored by the Classification Labelling and Packaging (CLP) Regulation, which standardises classification, labelling and packaging rules [118].

In the United States (US):

- The Occupational Safety and Health Administration (OSHA) provides a dedicated federal baseline for storage and handling of anhydrous ammonia systems, presenting a direct compliance reference for facility-level requirements [119];
- At the community-risk and emergency-program level, EPA's Risk Management Program rules define regulated-substance program duties, where applicability thresholds are met, shaping prevention measures expectations and emergency coordination for high-inventory sites [120];
- For transport-related compliance, the Department Of Transportation (DOT) hazardous material table functions as a regulatory index, linking shipping descriptions and hazard classes to handling, labelling/packaging, and movement conditions that logistics nodes must operationalise [121].

For the selected Asian jurisdictions:

- In Japan, the High Pressure Gas Safety Act (HPGSA) operates as an umbrella statute governing production, storage, transportation, sale and related handling of high-pressure gases, therefore providing the principal legal anchor for infrastructure compliance [122];

- In the Republic of Korea, the High-Pressure Gas Safety Control Act (HPGSCA) similarly structures legal controls across production, storage, transportation, sale and use of high-pressure gases, forming a comparable foundation for ammonia logistics governance [123];
- In Singapore, major hazardous installations are subject to a registration regime under the Workplace Safety and Health (Major Hazard Installations) Regulations (WSH (MHI) Regulations), while chemical-control requirements relevant to storage and handling are administered by the National Environment Agency (NEA) under the Environmental Protection and Management Act (EPMA) and its Environmental Protection and Management (Hazardous Substances) Regulations (EPM (HS) Regulations) [124], [125].

Beyond prescriptive legal instruments, infrastructure compliance cases may rely on recognised engineering codes to evidence accepted practice for equipment design, construction and integrity arguments, supporting conformity and integrity justification within regulated regimes [116], [126].

In this technical layer, the most relevant reference points can be presented as follows:

- International Organisation for Standardisation (ISO): ISO 16528-1 provides performance requirements for pressure vessels that can be used as benchmark alongside national or regional codes [127];
- European Union (EN/harmonised standards): the standard-to-regulation link is often operationalised through harmonised European standard (EN), which are presented as tools to demonstrate conformity with relevant EU requirements, including the pressure equipment domain under the PED framework [116], [126];
- American Society of Mechanical Engineers (ASME): ASME Boiler and Pressure Vessel Code (BPVC) is a US-origin code family and is used as an engineering basis for pressure-containing equipment within regulated environments [128].

Table 21 presents the cross-jurisdiction summary of legal anchors and standards discussed above for fixed installations and for storage, transport and transfer interfaces.

Table 21 - Comparison of major regulatory references and technical-standard anchors for ammonia infrastructure in selected jurisdictions, covering site safety, transport, equipment integrity, and environmental/chemical control.

Jurisdiction	Major-accident / site safety [Ref.]	DG transport / movement anchor [Ref.]	Equipment / integrity anchor [Ref.]	Environmental / chemical-control anchor [Ref.]
EU	Seveso III [115]	Directive 2008/68/EC [114]	PED [116]; Harmonised standards (EN ISO) [126]	IED [117]; CLP [118]
US	OSHA [119]	DOT hazardous materials table [121]	ASME BPVC [128]; ISO 16528-1 [127]	EPA RMP [120]
Japan	HPGSA [122]	HPGSA [122]	HPGSA [122]; ISO 16528-1 [127]	HPGSA [122]
Republic of Korea	HPGSCA [123]	HPGSCA [123]	HPGSCA [123]; ISO 16528-1 [127]	HPGSCA [123]
Singapore	WSH MHI [124]	-	ISO 16528-1 [127]	EPMA NEA [125]

In conclusion, ammonia logistics infrastructure is governed by a layered and diversified compliance stack in which IMO instruments set the maritime interface baseline, while regional or national frameworks impose site safety, equipment conformity and environmental/chemical-control obligations that define how terminals and hubs must be permitted, documented and operated.

Transport modes are also regulated within this framework, but through a combination of international maritime rules and jurisdiction-specific dangerous-goods provisions governing inland movements and operational conditions, including loading/unloading and transfer activities. This results in a broadly consistent set of transport-related conditions that logistics nodes must implement, although the applicable legal instruments differ by transport mode and jurisdiction.

Recognised engineering codes are not substitutes for legal compliance but can provide the defensible technical basis used to support conformity and integrity arguments within these regulatory regimes.

4.5. Existing infrastructure and future expansions

This section provides a concise overview of the current global ammonia infrastructure, developed primarily for existing markets, and the main expansion signals emerging from announced and under-development assets. The focus is on infrastructure categories that can be mapped and tracked consistently at global scale, namely fixed assets (terminals/storage and pipelines) and mobile assets (maritime fleet). Road and rail are mentioned only as supporting modes, given the limited availability of global datasets on fleet size and expansion plans.

A globally distributed storage and terminal network is already in place. As of 2025, one dataset tracks 925 ammonia terminals worldwide, including both operational assets and facilities under development, providing a robust baseline of where infrastructure is concentrated and where additions are appearing (Figure 60).

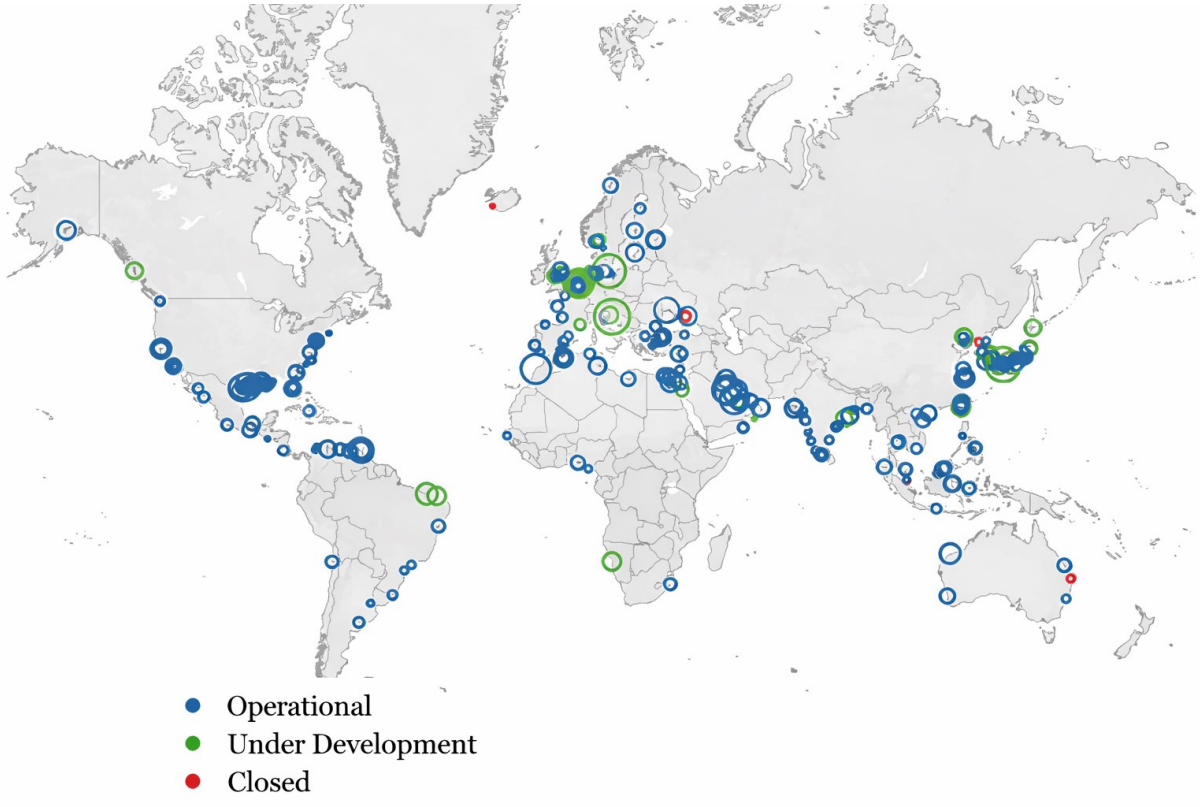

Figure 60 - Global ammonia terminals: operational, under-development and closed assets (inland, coastal and ports) [11].

The same source identifies a subset of 331 terminals located in industrial ports and estimates an aggregate throughput potential of 105 Mt/y, under the assumption of 25 turnovers per year, offering a practical benchmark to contextualise the scale of existing

port-side infrastructure within the broader logistics system. Accordingly with this port-centric footprint, the United States stands out for the scale of its storage system: total storage capacity is reported at 6.5 Mt, of which 2.9 Mt in coastal terminals and 3.7 Mt inland, suggesting an established distribution structure that already supports significant ammonia flows [11].

Transport similarly rests on an established operational base. In 2024, about 45 Mt of ammonia were moved domestically and internationally across multiple modes, of which 17-20 Mt were transported internationally by gas carriers. Regarding seaborne logistics, the existing dedicated ammonia carrier fleet includes 81 vessels, while a substantially larger pool of about 508 ocean-going vessels is considered technically capable of carrying ammonia even if most currently serve LPG trades (Figure 61).

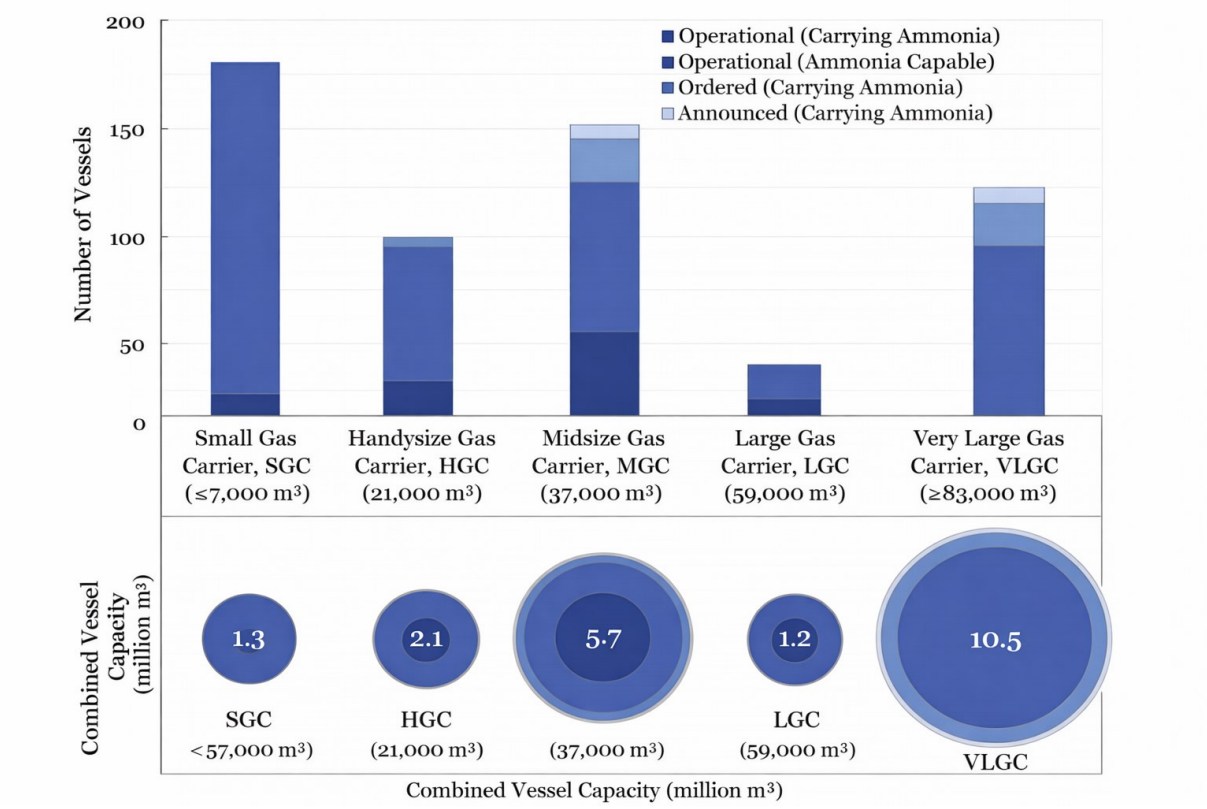

Figure 61 - Ammonia carrier fleet and ammonia-capable vessels: operational base and near-term additions (by vessel class and status) [11].

The same source reports a near-term expansion pipeline of 63 ammonia carriers, of which 41 already ordered, and specifies that the orderbook includes a substantial share of VLGCs, aligning with future high-volume import/export corridors.

As ammonia trade becomes increasingly linked to marine fuel adoption, bunkering emerges as a distinct infrastructure requirement rather than a simple extension of

storage, as implementation is shaped by port-space constraints, the need for dedicated fuel-transfer systems, and safety-driven operational arrangements [6]. In this context, Singapore is often cited as an early mover where feasibility studies and pilot-oriented initiatives combine port governance, shipowners, and technology providers, reflecting an approach centred on demonstrations, operational learning, and safety development [9]. A complementary demand signal comes from a fleet-oriented snapshot that tracks 415 ammonia-fuelled and ammonia-ready vessels, of which 154 fuelled and 261 ready (Figure 62).

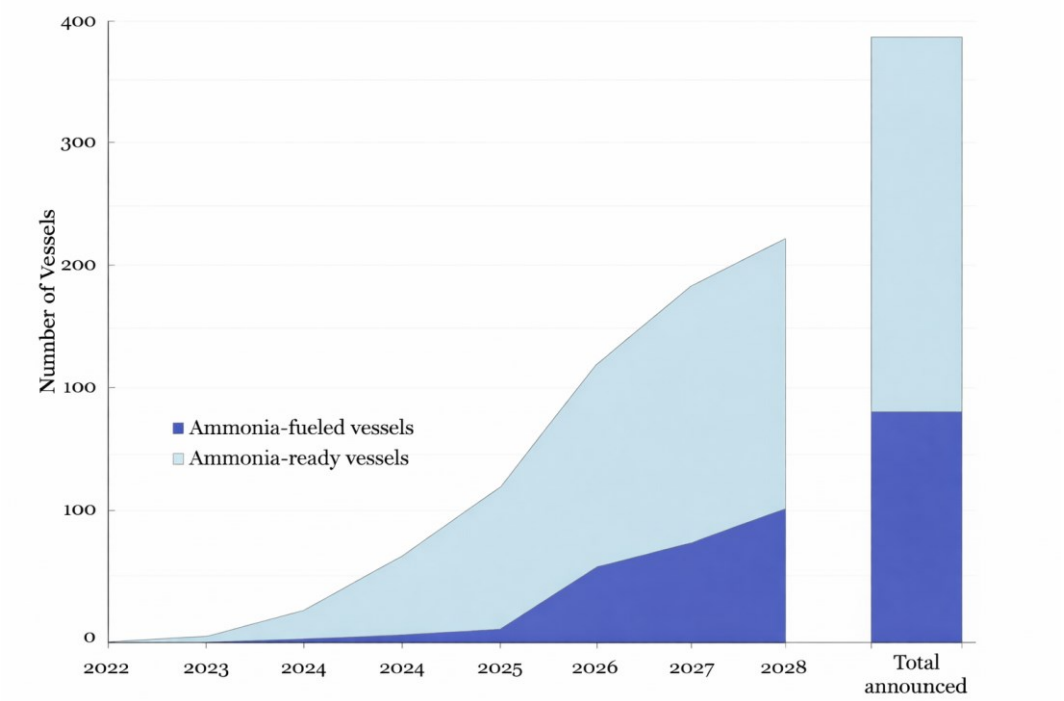

Figure 62 - Announced ammonia-fueled and ammonia-ready vessels: pipeline to 2028 and total announced [129].

In other words, bunkering-related investment and planning increasingly evolve with fleet commitments, and early deployment tends to concentrate in a limited set of highly organised port hubs. Moreover, a standard timeline is already defined, with IMO guidance and an IGC code change entering into force on 1 July 2026 to allow ammonia to be used also as a fuel, linking bunkering investment decisions to a regulatory milestone [129].

By contrast, pipeline infrastructure represents a more geographically concentrated but established option for large-volume inland transport where demand centres justify dedicated corridors. It is reported that approximately 8000 km of ammonia pipelines exist worldwide, with the United States accounting for more than half [6]. At the same

time, global infrastructure tracking highlights that some long-distance ammonia pipelines already exist, supporting the view that this mode can function as a mature backbone in specific regions rather than a purely greenfield option [11].

For the United States, this concentration is clearly illustrated in Figure 63, which visually connects inland demand clusters to existing distribution corridors. In addition to the backbone lines, the installed base as including more than 10000 storage tanks, reinforcing the interpretation of a mature logistics network with dense storage nodes connected to long-distance pipelines and transport corridors [6], [11].

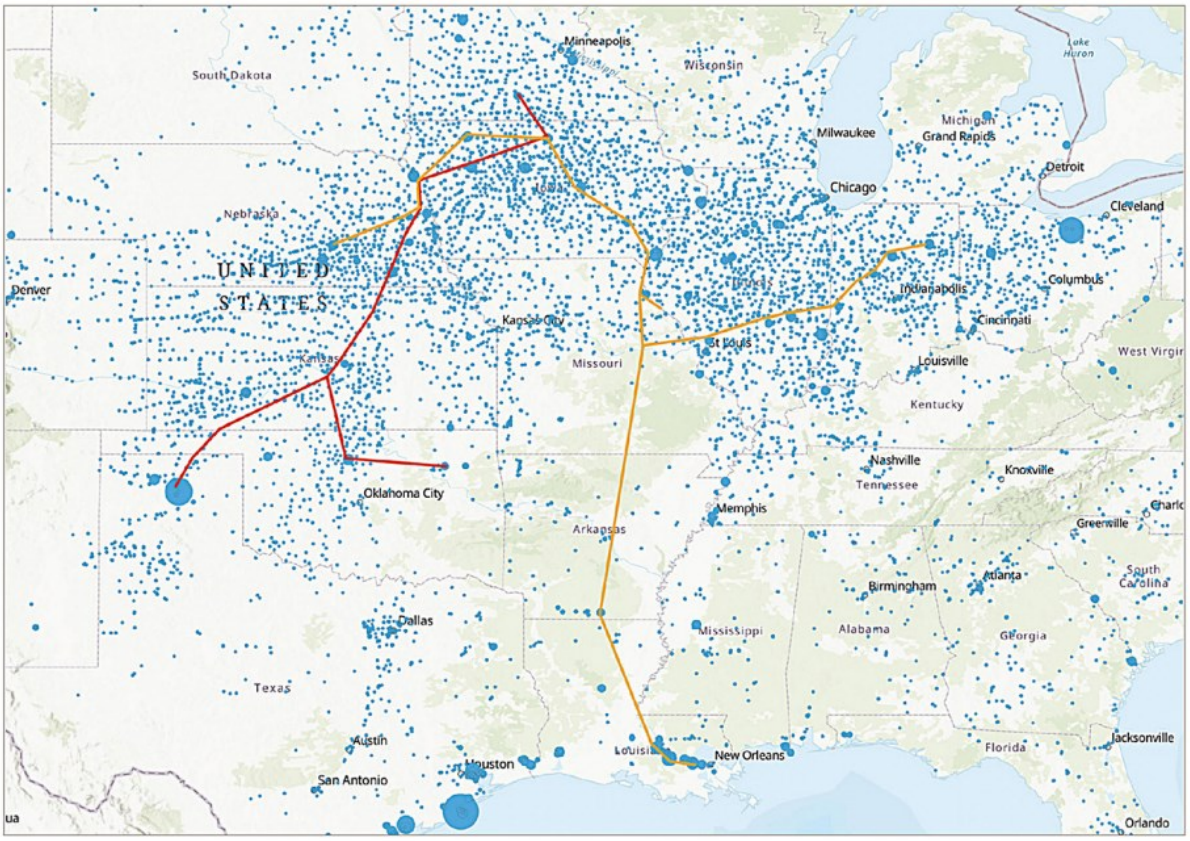

Figure 63 - United States: illustrative ammonia pipeline network and storage sites/terminals [6].

Regarding Europe, available evidence suggests that systems are typically shorter and clustered around industrial sites, while dedicated long-distance corridors are discussed in relation to future import-to-inland connections; benchmark values and design/safety framing for large-scale clean ammonia pipelines are reported and further contextualised in literature [9], [106]. In this context, the European pipeline footprint is often described as “many but short”, typically between 1-12 km: most lines serve intra-cluster connections rather than long-range distribution [6]. IRENA’s Innovation Outlook also reports an Italian ammonia pipeline of 74 km, which provides a concrete

example of a longer European segment compared to typical lines [9]. A related implication is that, where pipelines are short and localised, inland distribution beyond the port gate is more likely to rely on complementary modes, such as road and rail.

To clarify the geographical concentration of long-distance ammonia pipelines at global scale, the literature also highlights a very long corridor of roughly 2400 km (Togliatti-Odesa pipeline), which helps interpret why, outside a few backbone systems, most of the remaining network length is distributed across shorter, localised industrial lines [9], [106].

Finally, road and rail remain relevant as enabling modalities for inland distribution, especially for connecting terminals and industrial users, but consistent global datasets on fleet size and announced expansions are limited compared to those available for terminals, shipping, and major pipelines. For this reason, this chapter prioritises the asset categories that can be systematically mapped and tracked at global scale, while project-level granularity on announced developments is provided in the regional sections that follow.

Overall, the global snapshot suggests that a relatively strong installed base exists, especially in port terminals and maritime logistics, while near- to mid-term expansion is most visibly expressed through port-centric terminal additions, fleet growth (combining dedicated carriers and ammonia-capable capacity), bunkering pilots clustered in a small number of port hubs (with Singapore as a recurrent reference case), and selective pipeline corridors where inland scale and geography justify dedicated corridors [6], [9], [11], [106], [129].

4.5.1. United States

USA projects' evidence on ammonia storage and transport is currently most visible along the Gulf Coast, with initiatives typically framed as export-linked configurations (terminal storage and port logistics explicitly coupled to supply projects). Table 22 summarises the most relevant publicly documented projects using consistent milestones, such as Final Investment Decision (FID), announced, study phase.

Table 22 - Project registry of ammonia infrastructure initiatives in the United States (status reflects publicly stated milestones; financing is reported only when explicitly disclosed in primary sources).

Project	Asset type	Location and Developers	Status	Funding (*)	Ref.
Blue Point	Production + export terminal	Louisiana, US JERA; CF Industries; Mitsui & Co.	FID	N/D	[130]
St. Charles Clean Fuels	Terminal/storage + Production facility	Louisiana, US IMTT; SC Clean Fuels; CIP; SFG	ANN	Grant + incentives	[131], [132]
Ten08 Clean Ammonia	Supply chain + shipping	U.S. Gulf Coast Ten08 Energy; Navigator Gas; Attis CE	ANN	N/D	[133]
Corpus Christi Clean Ammonia (JSA)	Integrated export concept (Production + port)	Texas, US RWE; LOTTE Chemical; Mitsubishi Corp.	ANN	N/D	[134]

(*) Funding as stated in sources.
ANN = announced; FID = final investment decision; N/D = not disclosed.

Blue Point is anchored by an FID and is described as targeting approximately 1.4 Mt/y, with commercial start-up planned for 2029; while Mitsui states that construction will begin in 2025, CF Industries indicates that pre-construction activities start in 2025 and that construction of the ammonia production facility is expected to begin in 2026 [130], [135].

St. Charles is described at proposal stage but indicates an intended scale of roughly 2.8 Mt/y and includes explicit references to terminal-linked storage and export services, while disclosing a limited set of state incentives rather than a full financing package [131], [132].

Ten08 is documented through a US Securities and Exchange Commission (SEC) filing, describing an integrated clean-ammonia production and export concept that explicitly includes international seaborne transportation to customers in Europe and Asia; it is therefore treated as an announced commercial configuration rather than a committed terminal build-out [133].

Similarly, the Port of Corpus Christi initiative is framed as a Joint Study Agreement (JSA) focused on evaluating an integrated export concept and related supply-chain arrangements; this supports its classification as announced (study phase) rather than an investment-backed construction project [134].

Overall, the U.S. sample is most readily documented along Gulf Coast, through export-oriented configurations, with one project at FID level and the remainder at announced or study stages. Financing disclosure is partial and is therefore reported as not disclosed when not explicitly stated.

4.5.2. Europe

European project evidence for ammonia storage and transport expansion is currently most visible in Northwest Europe, where import-oriented initiatives concentrate in major port hubs and progress through structured milestones supported, in some cases, by EU funding disclosed in primary sources. Figure 64 provides a regional snapshot of operational and under-development terminals.

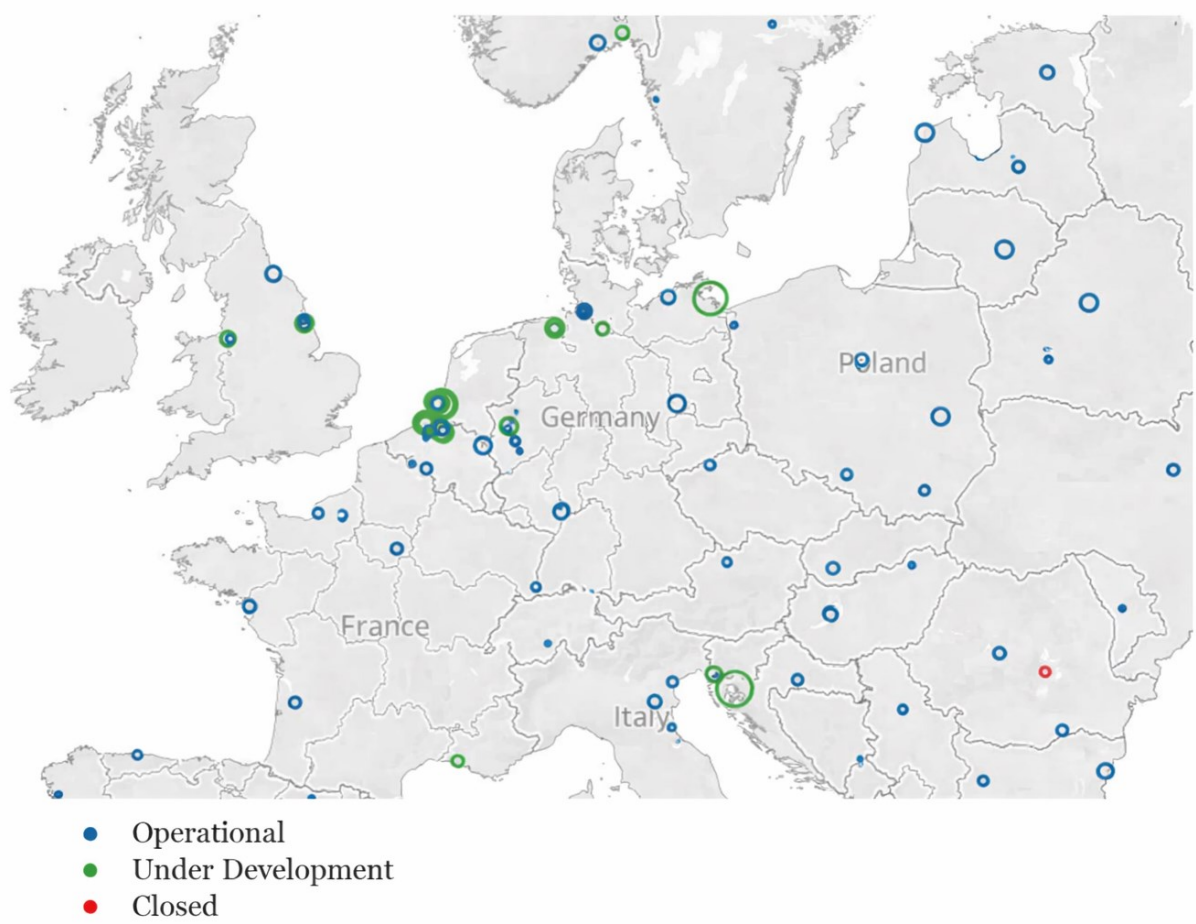

Figure 64 - Ammonia terminals in Europe (operational, under-development and closed assets) [11].

Table 23 summarises the project registry using publicly stated milestones, such as Pre-Front-End Engineering Design (Pre-FEED), Front-End Engineering Design (FEED), and announced build plans.

Table 23 - Project registry of ammonia infrastructure initiatives in West Europe (status reflects publicly stated milestones; financing is reported only when explicitly disclosed in primary sources).

Project	Asset type	Location and Developers	Status	Funding (*)	Ref.
ACE Terminal (Maasvlakte)	Import terminal + storage	Netherlands (Port of Rotterdam – Maasvlakte) Gasunie; HES Int.; Vopak	Pre-FEED	CEF Energy grant (study): 25.62 million €	[136], [137]
NH3 Antwerp Terminal	Import terminal + in-port pipeline	Belgium (Port of Antwerp-Bruges) (Advario site), Fluxys; Advario	FEED	N/D	[138]
Green Wilhelmshaven (ammonia import terminal component)	Import terminal + storage (rail loading)	Germany - Wilhelmshaven, Uniper	Pre-FEED	CEF Energy grant (studies): 10.63 million €	[137], [139], [140]
RWE Brunsbüttel Ammonia Terminal	Import terminal + port logistics	Germany - Brunsbüttel, RWE	ANN	N/D	[141]

(*) Funding as stated in sources.
Pre-FEED = Pre-Front-End Engineering Design; FEED = Front-End Engineering Design; N/D = not disclosed.

Rotterdam is presented as the leading hub, with "under development" throughput reported at 18.1 Mt/y under the assumption of 25 turnovers per year, and is linked to updated Dutch safety/handling guidance (PGS-12), suggesting that regulatory alignment is treated as a parallel workstream to physical capacity expansion [11].

Second, the Brunsbüttel announcement states an initial import volume on the order of 0.3 Mt/y from 2026 and describes downstream conversion (cracking) and pipeline integration aligning with the broader European framing of import terminals as multi-component systems rather than stand-alone storage [6], [141].

Overall, the registry indicates a hub-based build-out pattern in Northwest Europe, spanning from Pre-FEED studies supported by Connecting Europe Facility (CEF) grants, FEED-stage progression, and announced build plans.

4.5.3. Eastern Asia

In Eastern Asia, project evidence for ammonia storage and transport expansion is most visible in Japan and South Korea, where initiatives are framed around port-led import bases and associated receiving, storage and transfer functions. Figure 65 provides a regional snapshot of operational and under-development terminals [11].

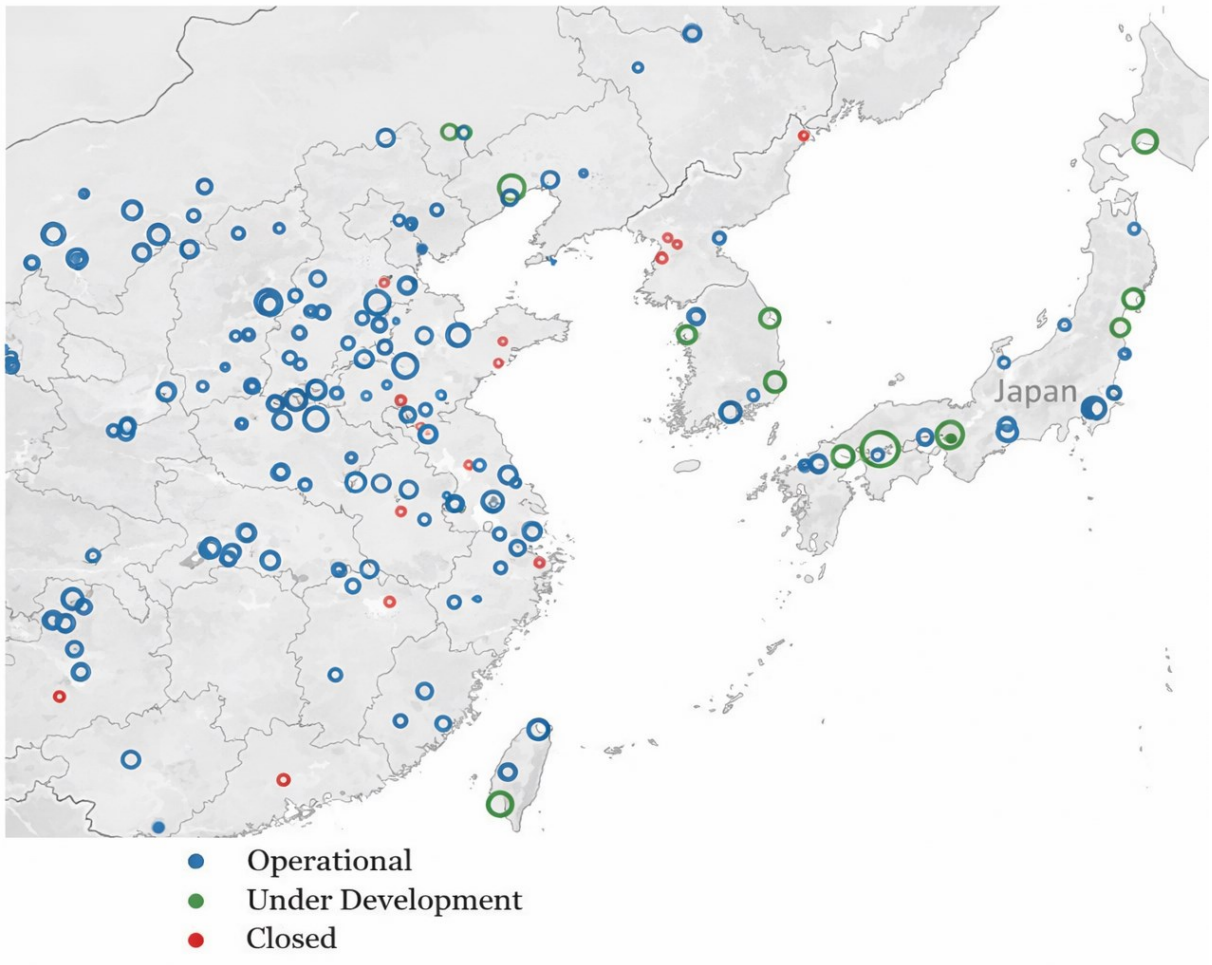

Figure 65 - East Asia ammonia terminals (operational, under-development and closed assets) [11].

Japan's import trajectory for power-sector applications is described as rising from roughly 0.2-0.3 Mt/y in the early 2020s to roughly 3 Mt/y in 2030 and 30 Mt/y in 2050. Operational storage is quantified as able to process 7.1 Mt/y, increasing to 20.1 Mt/y when under-development capacity is included, under the assumption of 25 turnovers per year [11].

Table 24 summarises the project registry of Japan.

Table 24 - Project registry of ammonia infrastructure initiatives in Japan (status reflects publicly stated milestones; financing is reported only when explicitly disclosed in primary sources).

Project	Asset type	Location and Developers	Status	Funding (*)	Ref.
Council for utilising Namikata Terminal as a Hub for introducing Fuel Ammonia	Terminal/storage retrofit	Japan - Namikata Terminal (Ehime), Mitsubishi Corporation	ANN	N/D	[142]
Basic Study on the Establishment of Ammonia Supply System in the Shunan Industrial Complex	Terminal/storage + industrial logistics	Japan - Shunan Industrial Complex (Tokuyama area), Tokuyama Corporation	ANN	N/D	[143]

(*) Funding as stated in sources.
ANN = announced; N/D = not disclosed.

Namikata initiative assumes to handle roughly 1 Mt/y by 2030, while the Shunan basic study targets over 1 Mt/y by 2030, consistent with early build-out centred on a small number of terminal/industrial nodes [142], [143].

South Korea similarly positions ports and industrial clusters as key nodes for scaling receiving and handling capacity for energy-related imports beyond existing chemical-industry demand. Demand-side support is described through an ammonia-for-power auction mechanism (first auction concluded in December 2024, with a further round in 2025), strengthening the commercial rationale for new import terminals and associated logistics services [11].

Table 25 summarises the project registry of South Korea.

Table 25 - Project registry of ammonia infrastructure initiatives in South Korea (status reflects publicly stated milestones; financing is reported only when explicitly disclosed in primary sources).

Project	Asset type	Location	Status	Funding (*)	Ref.
Samsung C&T ammonia import terminal for co-firing power generation	Import terminal + storage	South Korea Gangwon-do (Samcheok area), Samsung C&T (EPC)	UC	N/D	[144]
Ulsan City–Hyundai Oil Terminal ammonia storage facility and infrastructure expansion (Namsin Port Phase 2)	Storage expansion + port transfer	South Korea - Namsin Port (Ulsan), Ulsan Metropolitan City; Hyundai Oil Terminal	ANN	N/D	[145]

(*) Funding as stated in sources.
ANN = announced; UC = Under construction; N/D = not disclosed.

For the Samsung C&T project, the most relevant signal is its stated under-construction status within an Engineering Procurement and Construction (EPC) framework for an ammonia import terminal supporting co-firing fuel supply, with completion planned for July 2027, indicating a near-term delivery compared to announced expansion concepts [144].

Whereas the Ulsan project specifies 80000 m^3 of storage across two tanks, a dolphin pier with two berths, and approximately 4 km of transfer pipeline, with completion planned by December 2028 and a stated handling capacity of 1.25 Mt/y once completed [145].

Regarding Singapore, The Energy Market Authority of Singapore (EMA) reports that a consortium led by Keppel has been appointed to conduct the next phase of a low- or zero-carbon ammonia power generation and bunkering solution on Jurong Island. The release indicates FEED studies for both power generation and bunkering, with no FID at the time of publication, and reports a targeted power generation range of 55-65 MW and an ammonia bunkering throughput of at least 0.1 Mt/y [146].

Overall, the Eastern Asia registry indicates a hub-based build-out pattern: Japan and South Korea are advancing terminal- and storage-centred import-base developments across announced studies/retrofits and under-construction assets, while Singapore is positioned at FEED stage for an integrated power-and-bunkering concepts.

5 Critical assessment of infrastructure expansion scenarios

This chapter provides a critical assessment of the scalability at global level of the infrastructure required to accommodate the growth of ammonia flows across three logistics segments: terminal storage, seaborne and pipeline transport. The aim is not only to quantify how much additional infrastructure is required in 2030 and 2050, under IRENA scenarios, but also to assess how feasible such expansion is, considering both physical and non-physical constraints. These quantitative estimates are intended as order-of-magnitude requirements under transparent assumptions.

5.1. Methods

Infrastructure requirements are estimated using a top-down approach, starting from the projected global ammonia demand in the IRENA's scenarios (1.5°C and Stated Policies) for 2030 (short-term) and 2050 (long-term). IRENA's Innovation Outlook is adopted as the primary quantitative source because it provides a consistent decomposition between existing markets and new uses, as well as explicit sizing benchmarks for the emerging ammonia economy (reported for 2050 under the 1.5°C Scenario), which are needed to implement the scaling procedure used in this chapter. Storage is treated as a capacity stock (Mt), whereas seaborne and pipeline metrics represent the annual throughput (Mt/y). Table 26 reports the demand split between the two components for the scenarios under scrutiny and constitutes the quantitative input for the infrastructure sizing procedure.

Table 26 - Projected ammonia demand (Mt/y) in 2030 and 2050 under IRENA scenarios (1.5°C and Stated Policies), by existing- and new-use markets [9].

	(1.5°C)		**Stated Policies**	
Demand by end-use market	**2030**	**2050**	**2030**	**2050**
Existing uses [Mt/y]	223	334	223	334
New uses [Mt/y]	34–36	354	16–18	217

For existing uses, storage needs and baseline logistics flows are assumed to scale linearly with the existing uses demand relative to a 2024 baseline; in this implementation, existing-market demand is taken directly from IRENA and treated as scenario-invariant across the two pathways because differences between scenarios are driven primarily by the uptake of new uses. Scaling is applied consistently across the three infrastructure segments, using the 2024 baselines reported in Table 27.

Table 27 - 2024 baseline values for storage capacity, seaborne and pipeline throughput.

Baseline variable (2024)	Units	Value	Definition [Ref.]
Port/Terminal capacity	Mt	6.5	Global terminal capacity converted to mass using liquid ammonia density (See Appendix B) [147]
Seaborne throughput	Mt/y	15–20	Range for "existing markets" seaborne ammonia trade [147]
Pipeline throughput	Mt/y	4.3	Proxy sum of major assets (US Midwest, Italy and Togliatti-Odessa) [148], [149]

For new uses, the analysis relies on IRENA's 2050 sizing points in the 1.5°C scenario for both storage capacity and seaborne transport. Since equivalent values are not reported for the Stated Policies scenario, the same benchmarks are adopted as a first-order proxy and rescaled using the ratio of new-use demand in 2050; the resulting requirements are then scaled to 2030 in proportion with the new-use demand ratio. This benchmark transfer is an explicit approximation: it assumes that the benchmark points reflect broadly comparable operational design choices (storage coverage in days and vessel utilisation assumptions) across pathways, while scenario differences are captured primarily through volume scaling; the implications are discussed in Appendix B.

Operationally, new-use seaborne throughput and storage capacity are obtained by applying two constant shares inferred from IRENA's 2050 benchmarks (1.5°C Scenario) to new-use demand in 2030 and across scenarios. This constant allocation is used only to obtain an internally consistent first-order split between seaborne and non-seaborne flows. Therefore, it should not be interpreted as a precise representation of future trade patterns, which may vary with regional supply-demand balances, the location of production hubs, and the development of domestic distribution networks.

Similarly, pipeline requirements combine a scaled existing-market component and a new-use component linked to seaborne flows through a baseline pipeline-to-seaborne ratio, calibrated from 2024 proxy values. This reflects that major ammonia pipelines

typically act as port-hinterland connectors and are frequently associated with import/export terminals; therefore, new-use pipeline throughput is modelled as proportional to new-use seaborne throughput. Given the strong regional dependence of pipeline deployment (siting constraints, permitting timelines, safety distances and network integration), pipeline results should be interpreted as indicative and are reported as a range driven by baseline proxy uncertainty. The full procedure and assumptions are reported in Appendix B.

Table 28 summarises the total requirements for each segment, computed by applying the above-mentioned scaling logic.

Table 28 - Ammonia infrastructure requirements (storage capacity, seaborne and pipeline throughput) derived from projected demand, 2030 and 2050 under IRENA scenarios (1.5°C and Stated Policies).

		1.5°C		Stated Policies	
Infrastructure segment (required)	**Units**	**2030**	**2050**	**2030**	**2050**
Port/industrial storage capacity	Mt	11.2–11.4	48.3	9.3–9.5	34
Seaborne transport	Mt/y	46.4–54.0	326.4–335.2	31.2–38.7	210.3–219.1
Pipeline transport	Mt/y	11.2-13.8	72.1-93.6	8-9.4	47.1-60.3

Finally, the scaling ratios (SRs) can be computed following Equations (19), (20) and (21), for storage capacity, seaborne transport and pipeline transport, respectively:

$$SR^{s}_{storage,t} = \frac{S^{s}_{t}}{S_{2024}} \quad [-] \tag{19}$$

$$SR^{s}_{sea,t} = \frac{T^{s}_{sea,t}}{T_{sea,2024}} \quad [-] \tag{20}$$

$$SR^{s}_{pipe,t} = \frac{T^{s}_{pipe,t}}{T_{pipe,2024}} \quad [-] \tag{21}$$

where t stands for the timeline considered (2030 or 2050) and s stand for the IRENA scenario considered (1.5°C or Stated Policies).

5.2. Results

The following section reports the scaling ratios for port/terminal capacity, seaborne and pipeline throughput implied by the IRENA demand pathways. Even under the Stated Policies Scenario, which reflects the implementation of policies and targets already announced, global ammonia logistics must expand materially by 2030 and then accelerate further by 2050, while the 1.5°C scenario pushes the same system to a higher scale, highlighting the additional infrastructure required to be aligned with the decarbonisation targets.

Scaling ratios should be interpreted as order-of-magnitude indicators of bulk-handling capacity expansion, not as a deterministic project pipeline.

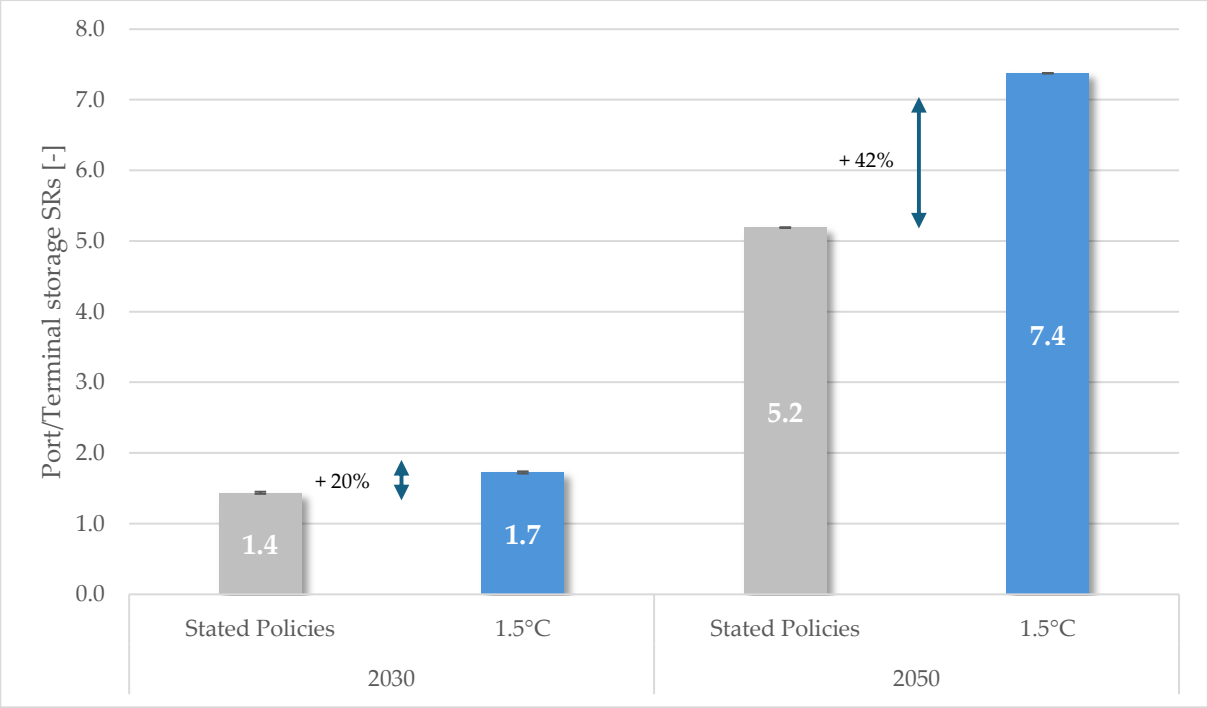

Figure 66 - Scaling ratios for global port/terminal storage capacity (baseline 2024) under IRENA Stated Policies and 1.5°C scenarios, for 2030 and 2050.

The storage scaling ratios (Figure 66) show that even the announced-policies trajectory requires a step-change in global port/terminal storage capacity by mid-century, while the 1.5°C scenario entails a materially larger expansion on top of already ambitious growth. This gap matters because Stated Policies can be interpreted as a closer proxy for "what is currently in motion"; therefore, the difference with 1.5°C is not incremental, but a second acceleration stage that must occur after 2030. This divergence mainly reflects the shift in storage's role: from fertiliser-oriented logistics

to global energy-system buffering, as ammonia is increasingly used as an energy- and hydrogen-carrier and must ensure continuity between variable supply chains and steady end-use demand. Required capacity therefore scales with the working inventory needed to smooth flows, not simply with annual demand (see Section 4.3).

The existing storage and terminal base does not automatically match the operational and spatial requirements associated to new uses, even in ports where ammonia handling is already established [150]. By mid-century, higher throughput requirements typically drive terminals toward large hub configurations built around high-throughput transport links, which tends to favour refrigerated storage and more stringent interface and safety layouts, increasing land take and design complexity (see Section 4.3 and 4.5).

The dominant physical bottleneck is primarily spatial: large, refrigerated ammonia tanks and associated safety boundaries, require substantial land availability inside or in proximity to ports and industrial zones, where space is already scarce and competing uses are high [9], [150]. Major ports can face explicit space constraints that limit either the expansion of existing terminals or the construction of new ones, and the constraint can intensify if additional conversion units, such as ammonia-cracking units for hydrogen conversion, are co-located inside the harbour [151].

These considerations also highlight a design trade-off: concentrating volumes in a few hub-scale terminals to exploit economies of scale or spreading capacity across multiple smaller nodes to reduce local siting pressure, at the cost of higher network coordination needs (see Section 4.3 and 4.5).

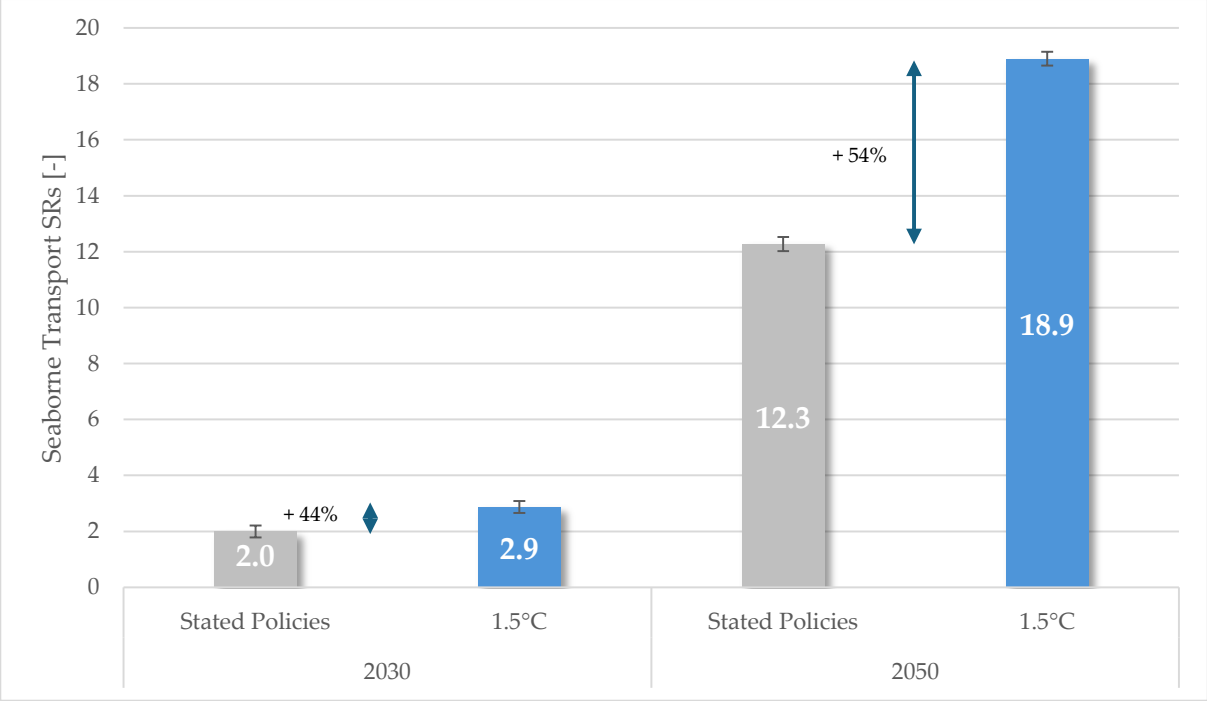

Figure 67 - Scaling ratios for global seaborne transport throughput (baseline 2024) under IRENA Stated Policies and 1.5°C scenarios, for 2030 and 2050.

Seaborne transport scaling ratios (Figure 67) are the steepest, implying that maritime trade is not a marginal add-on but a core enabling factor of the new ammonia economy, and the gap between scenarios again signals that the 1.5°C scenario requires a much faster expansion. Seaborne scaling is governed by corridor constraints: distance and port turnaround define cycle time, meaning that longer routes or slower operations increase fleet needs disproportionately relative to traded volumes (see Section 4.2.1).

Maritime shipping scale-up is physically constrained by two main bottlenecks: the availability of suitable gas carriers and the readiness of ports to berth and handle larger vessels with higher frequency [9], [150]. In the near term, scaling is paced by fleet availability, both newbuild deliveries and the retrofit pipeline. The dedicated ammonia fleet remains small and largely centred on mid-size units, skewed toward MGC rather than VLGC class capacity, while "ammonia capable" LPG carriers still require technical adaptations and slot availability, limiting throughput before port capacity becomes the dominant constraint (see Section 4.5).

Port-side infrastructure is also a limiting factor, because larger vessels require compatible deep-water berths and dedicated facilities, and the IEA explicitly links post-2030 expansion to the need for new deep-water ports and berthing facilities alongside new storage tanks to serve emerging trade routes [20].

Regional port-readiness evidence indicates that infrastructure and related enabling factors can be hindered for hydrogen-derivative supply chains, with stakeholder assessments in Australia and Japan placing infrastructure readiness below mid-scale levels, implying slow port-side ramp-up where trade corridors depend on those nodes [152].

Additionally, where ammonia is being considered as a shipping fuel, the bunkering infrastructure adds new interface problems, such as dedicated transfer arrangements, equipment and operating procedures that extend beyond conventional cargo handling layouts. If ammonia bunkering co-develops, ports effectively add a second, safety-critical set of operations on top of cargo handling, increasing interface complexity and reducing operational flexibility in terms of berth time, staffing and layout (see Section 4.2.1 and 4.3). Pilot demonstrations show that ship-to-ship transfer is feasible but remains demanding, since it requires controlled procedures and safety measures that translate into additional port-side assets and operational constraints during transfer activities [153]. A port-scale case study for Singapore associates low near-term bunkering uptake with "lack of infrastructure readiness" and "regulatory uncertainty", suggesting that port throughput related to bunkering is limited by infrastructure maturity even when demand signals emerge [154].

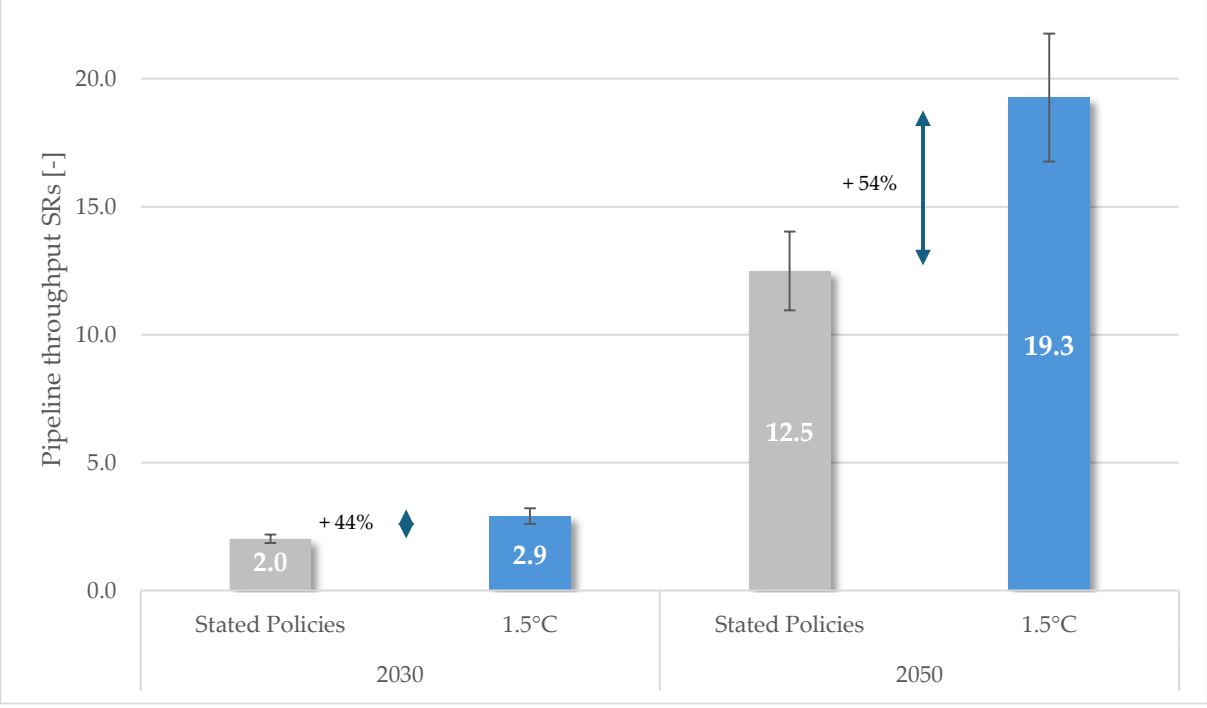

Figure 68 - Scaling ratios for global pipeline throughput (port-hinterland link; baseline 2024) under IRENA Stated Policies and 1.5°C scenarios, for 2030 and 2050.

Pipeline scaling ratios (Figure 68) grow substantially as well, but should be read as a range-based, first-order indicator rather than a deterministic buildout plan. It is anchored to a simple port-hinterland linkage: new-use pipeline throughput is obtained by applying a baseline pipeline-to-seaborne ratio (derived from 2024 proxy values) to the new-use seaborne throughput. This choice reflects that major ammonia pipelines are often developed to connect large terminals to inland industrial clusters and therefore must scale with traded volumes handled at ports. As a result, uncertainty here is structural: it is dominated by proxy baselines and regional deployment conditions rather than by short-term demand (see Appendix B).

The current throughput is constrained by the limited footprint of dedicated pipeline networks and by the need to build new long-distance corridors or retrofit existing ones where feasible [20], [150]. Pipeline scaling is ultimately constrained by safety, because toxicity-driven risk management (leak detection, sectional isolation and emergency-response integration) shapes routing and station design and can materially raise CAPEX beyond basic layouts (see Section 4.2.3) [155]. The build-out pace is physically and institutionally gated by corridor development (routing, rights-of-way, crossings and stations), and the IEA notes that even where announced pipeline volumes appear large on paper, only a small share reached final investment decision, delaying the translation of announced assets into buildable capacity.

Even when physical assets are technically deployable, expansion remains conditioned by high upfront capital investments and by demand-timing risk when infrastructure must be deployed before stable contracted volumes materialise [20], [153].

Permitting and regulatory compliance can become a schedule driver for terminals, because environmental and safety obligations require extensive studies and mitigation measures, and the permitting process for new terminals in Northwest Europe is described as time-consuming due to regulatory complexity and local acceptance constraints. In this sense, permitting, safety-case development and corridor approval processes function as de-risking milestones for both terminals and pipelines [151], [155].

Furthermore, regulatory readiness is particularly relevant to port and bunkering infrastructure, because the absence of fully standardised international regulatory frameworks for ammonia-as-fuel represents a major obstacle that delays commitment, while complicating standardisation of interfaces, procedures and liability expectations [153]. First-mover exposure to evolving and non-standardised ammonia-as-fuel regulations can affect bankability and timing of port-side bunkering investments [153], [154].

Coordinated planning across ports and hinterlands is crucial because constrained port space and the need for compatible berthing/storage layouts increase the risk of stranded terminal capacity, especially if build-out is not synchronised with corridor and offtake development [20], [151].

The financing challenge of anticipatory infrastructure remains central, because large-scale port and pipeline assets are capital intensive, and the IEA explicitly links slow progress to lengthy development process, resulting in the need to start planning early [20].

Infrastructure delivery is primarily constrained by policy, finance and execution rather than technical novelty, and public-private partnerships can be crucial to plan, develop and finance dedicated ammonia infrastructure. Moreover, life-cycle carbon-intensity accounting must be codified in standards and regulations to support market structures. Also, data-sharing and human-capital development can be cross-cutting constraints on scaling [6].

Overall, port terminals and seaborne transport emerge as global chokepoints, while pipeline build-out remains geography-driven and is likely to be uneven across regions.

6 Conclusions and future outlook

This thesis has investigated ammonia's relevance within the energy transition by adopting a perspective that combines production-side decarbonisation with practical deployment constraints. On the one hand, ammonia is already a major industrial commodity associated with significant CO_2-emissions under current production systems; therefore, decarbonising its production is an important mitigation lever even if ammonia's end-uses remain largely unchanged. On the other hand, ammonia is increasingly discussed as a potential low-emissions energy and hydrogen carrier, which implies additional volumes and new logistical patterns beyond today's established infrastructure capacity. In this context, the premise of the thesis is that decarbonising production is a crucial step, but it is not sufficient to achieve more ambitious decarbonisation goals: the ability to scale low-emissions ammonia depends also on whether the infrastructure can expand, adapt, and integrate to accommodate the required volumes for new uses.

To address this, the work has combined two complementary lines of analysis. First, it has developed a critical 3E analysis of conventional ammonia production pathways, comparing energy performance, environmental impacts (through LCA indicators), and economic aspects (focusing on LCOA). Second, it has reviewed key elements of ammonia infrastructure, logistics, and safety, and then proposed a scenario-based critical assessment of infrastructure scalability, using global scaling ratios as order-of-magnitude indicators to discuss expansion needs and potential constraints under energy-transition scenarios.

From the energy perspective, the 3E analysis suggests that conventional grey ammonia remains a meaningful benchmark in terms of energy performance. This outcome is consistent with the fact that conventional production has been deployed and optimised for decades and therefore embodies a level of technological maturity and incremental improvement that is not yet comparable with less established pathways. Within the scope and assumptions adopted in the reviewed literature, alternative pathways do not always exhibit strikingly different energy performance, and in several cases the differences appear moderate rather than structural. This finding does not imply that low-emission routes are energetically equivalent in all contexts, but it supports a cautious interpretation: energy performance alone may not be sufficient to

clearly separate pathways without considering boundary conditions and system configurations. From the environmental perspective, this thesis does not identify a clear "winner" across all LCA indicators: moving towards low-carbon production routes can reduce climate-related impacts; however, other impact categories may remain broadly unchanged or, in some cases, increase depending on the upstream energy mix, materials, resource requirements and modelling assumptions. In other words, the environmental profile of low-emission ammonia is not captured by a single indicator, and climate benefits do not automatically translate into uniform improvements across the full set of environmental dimensions considered. From the economic perspective, this thesis highlights cost as a central barrier for green ammonia in the conditions commonly reported in the literature, with the cost of electricity for electrolysis emerging as the main bottleneck in LCOA outcomes, while electrolyser CAPEX and other system-level parameters play a secondary role. In contrast, blue ammonia appears to offer comparatively lower costs and therefore may be considered a more accessible option in the short-to-medium term for reducing the emissions intensity of ammonia production. Within these limits, the 3E analysis supports a balanced message: production decarbonisation options can deliver meaningful climate-related improvements, but they involve trade-offs and constraints that depend on the pathway and on the assumptions adopted.

The discussion then moves from process-level performance to implementation conditions, considering whether low-emission ammonia can be handled and scaled within existing infrastructure, logistics, and safety requirements. The infrastructure review of ammonia logistics and safety measures suggests that many handling practices are mature in today's industrial context; however, its scaling, especially under scenarios that imply significant growth and altered trade flows, require nontrivial adaptation and expansion across multiple segments, including storage, terminals and interfaces, shipping capacity, and, in some contexts, pipelines. The critical assessment of infrastructure scalability, structured around scenario-based demand projections and expressed via global scaling ratios for 2030 and 2050, is intended as an approximate indicator rather than a detailed deployment plan. Within this framing, the analysis suggests that infrastructure expansion requirements could be substantial under more ambitious transition pathways and still challenging even under less ambitious ones. Taken together, these factors suggest that the key issue is not only how much infrastructure is needed, but also how and when it is developed relative to demand growth. In this sense, deployment may face a chicken-and-egg dilemma: infrastructure expansion requires confidence in future volumes, while demand growth depends on the prior availability of adequate logistics and handling capacity. Therefore, the main implication is not simply that more infrastructure

investment is required, but that infrastructure planning, permitting, and financing need to be coordinated early with production projects and demand-side adoption.

Overall, the thesis supports a system-level message: decarbonising production is necessary, but deployment at scale also depends on infrastructure and logistics being able to expand and integrate. The work draws on a broad set of sources, and its results should be read as comparative signals under stated assumptions; the infrastructure assessment addresses readiness and scale-up requirements rather than a full 3E quantification of infrastructure impacts, and the scaling ratios are meant to support discussion rather than forecasting.

Looking ahead, a natural next step would be to complement this global, scenario-driven perspective with regional or corridor-based assessments, where infrastructure geography, permitting regimes, and industrial clustering can be represented more explicitly. Future work could also translate scaling ratios into more operational, asset-level build-out needs and indicative timelines. Finally, greater attention to governance and enabling conditions, such as safety regulations, certifications, carbon-intensity accounting and investment de-risking mechanisms, could help identify which non-technical barriers most affect deployment timelines and which targeted measures could most effectively accelerate implementation.

Bibliography

[1] J. Griffin, 'A Study of Life-type Processes in Liquid Ammonia'.

[2] M. Zahedi, 'Safe Bunkering of Ammonia'.

[3] C. Cao *et al.*, 'A comprehensive comparison of green ammonia and green methanol from a full chain: production, transportation, storage and utilization', *Carbon Neutral Syst.*, vol. 1, no. 1, p. 8, Jun. 2025, doi: 10.1007/s44438-025-00009-9.

[4] G. Zamboni, F. Scamardella, P. Gualeni, and E. Canepa, 'Comparative analysis among different alternative fuels for ship propulsion in a well-to-wake perspective', *Heliyon*, vol. 10, no. 4, p. e26016, Feb. 2024, doi: 10.1016/j.heliyon.2024.e26016.

[5] 'TNO-2020-R11822'.

[6] 'icef2022_roadmap_Low-Carbon_Ammonia'.

[7] H. Ishaq and C. Crawford, 'Review of ammonia production and utilization: Enabling clean energy transition and net-zero climate targets', *Energy Convers. Manag.*, vol. 300, p. 117869, Jan. 2024, doi: 10.1016/j.enconman.2023.117869.

[8] International Energy Agency, *Ammonia Technology Roadmap: Towards more sustainable nitrogen fertiliser production*. OECD, 2021. doi: 10.1787/f6daa4a0-en.

[9] K. Rouwenhorst and G. Castellanos, *Innovation outlook: renewable ammonia*. Abu Dhabi], [Brooklyn: International Renewable Energy Agency ; Ammonia Energy Association, 2022.

[10] "https://www.usgs.gov/centers/national-minerals-information-center/nitrogen-statistics-and-information," [Online].

[11] Ammonia Energy Association, 'AEA-LEAD-Infrastructure-Executive-Summary-July-2025'. Jul. 2025. [Online]. Available: https://ammoniaenergy.org/wp-content/uploads/2025/07/AEA-LEAD-Infrastructure-Executive-Summary-July-2025.pdf

[12] T. text provides general information S. assumes no liability for the information given being complete or correct D. to varying update cycles and S. C. D. M. up-to-D. D. T. R. in the Text, "https://www.statista.com/topics/10358/ammonia/?srsltid=AfmBOoogIl2H4nuZ4kU8rJGLoNd3s7se5bDZmkKpeuoiFNCPcZrHP6Tm," [Online].

[13] J. Egerer, V. Grimm, K. Niazmand, and P. Runge, 'The economics of global green ammonia trade – "Shipping Australian wind and sunshine to Germany"', *Appl. Energy*, vol. 334, p. 120662, Mar. 2023, doi: 10.1016/j.apenergy.2023.120662.

[14] 'Argus Ammonia methodology', 2005.

[15] 'S&PGlobal_fertecon_specifications'.

[16] "https://www.spglobal.com/energy/en/news-research/latest-news/energy-transition/121125-low-carbon-ammonia-markets-firm-ahead-of-eu-carbon-border-rules," [Online].

[17] "https://www.spglobal.com/energy/en/news-research/latest-news/energy-transition/051023-interactive-ammonia-price-chart-natural-gas-feedstock-europe-usgc-black-sea," [Online].

[18] "https://webstat.banque-france.fr/en/themes/exr,EXR.M.USD.EUR.SP00.E," [Online].

[19] 'WorldEnergyOutlook2025'.

[20] 'GlobalHydrogenReview2025'.

[21] 'EnergyTechnologyPerspectives2024'.

[22] 'ha-_1_1_e_12_150dpi_nb'.

[23] '2022-07 Low-Carbon Hydrogen from Natural Gas Global Roadmap'.

[24] H. Kim, A. Lee, and H. Lim, 'Decision making with the deterministic judgment of urea production with various hydrogen sources: technical, economic, and environmental aspects', *Green Chem.*, vol. 24, no. 21, pp. 8412–8423, 2022, doi: 10.1039/d2gc01936a.

[25] V. Pattabathula, 'Ammonia', in *Kirk-Othmer Encyclopedia of Chemical Technology*, 1st edn, Kirk-Othmer, Ed., Wiley, 2019, pp. 1–33. doi: 10.1002/0471238961.0113131503262116.a01.pub4.

[26] J. Lewnard, 'Overview of ARPA-E Methane Pyrolysis Program and Possible Future Directions'.

[27] S. Iftikhar *et al.*, 'LaNixFe1−xO3 as flexible oxygen or carbon carriers for tunable syngas production and CO2 utilization', *Catal. Today*, vol. 416, p. 113854, Apr. 2023, doi: 10.1016/j.cattod.2022.07.022.

[28] D. Wendt, L. Knighton, and R. Boardman, 'High Temperature Steam Electrolysis Process Performance and Cost Estimates', INL/RPT-22-66117-Rev000, 1867883, Mar. 2022. doi: 10.2172/1867883.

[29] 'AEA-LEAD-Plants-Executive-Summary-May-2025'.

[30] A. M. O. Mohamed, I. G. Economou, and Y. Bicer, 'Navigating ammonia production routes: Life cycle assessment insights for a sustainable future', *Curr. Opin. Green Sustain. Chem.*, vol. 49, 2024, doi: 10.1016/j.cogsc.2024.100947.

[31] "https://ammoniaenergy.org/articles/novel-ammonia-production-technologies-catalysts-sorbents-electrochemistry-other-technology-pathways/," [Online].

[32] "https://ammoniaenergy.org/articles/a-road-ahead-via-lithium-mediated-electrochemical-nitrogen-reduction/," [Online].

[33] R. D. Milton and S. D. Minteer, 'Nitrogenase Bioelectrochemistry for Synthesis Applications', *Acc. Chem. Res.*, vol. 52, no. 12, pp. 3351–3360, Dec. 2019, doi: 10.1021/acs.accounts.9b00494.

[34] H. Hosseini, 'Dielectric barrier discharge plasma catalysis as an alternative approach for the synthesis of ammonia: a review', *RSC Adv.*, vol. 13, no. 40, pp. 28211–28223, 2023, doi: 10.1039/D3RA05580A.

[35] A. Wu *et al.*, 'Direct ammonia synthesis from the air via gliding arc plasma integrated with single atom electrocatalysis', *Appl. Catal. B Environ.*, vol. 299, p. 120667, Dec. 2021, doi: 10.1016/j.apcatb.2021.120667.

[36] C. Jordan-Peters, "https://research.csiro.au/hyresearch/ammoniac-a-chemical-looping-based-process-for-production-of-green-ammonia/," [Online].

[37] A. Thomas, "https://trace.org.au/promising-results-as-ammoniac-scales-up/," [Online].

[38] C. Zuo, Q. Su, and L. Yu, 'Research Progress in Composite Materials for Photocatalytic Nitrogen Fixation', *Molecules*, vol. 28, no. 21, p. 7277, Oct. 2023, doi: 10.3390/molecules28217277.

[39] C. H. Kim, J. Kim, F. Hollmann, and C. B. Park, 'Photoelectrocatalytic N2 fixation and C-H oxyfunctionalization driven by H2O oxidation', *Appl. Catal. B Environ.*, vol. 336, p. 122925, Nov. 2023, doi: 10.1016/j.apcatb.2023.122925.

[40] H. Xu *et al.*, 'Electrochemical ammonia synthesis through N2 and H2O under ambient conditions: Theory, practices, and challenges for catalysts and electrolytes', *Nano Energy*, vol. 69, p. 104469, Mar. 2020, doi: 10.1016/j.nanoen.2020.104469.

[41] J. Chen, H. Cheng, L.-X. Ding, and H. Wang, 'Competing hydrogen evolution reaction: a challenge in electrocatalytic nitrogen fixation', *Mater. Chem. Front.*, vol. 5, no. 16, pp. 5954–5969, 2021, doi: 10.1039/D1QM00546D.

[42] S. Z. Andersen *et al.*, 'A rigorous electrochemical ammonia synthesis protocol with quantitative isotope measurements', *Nature*, vol. 570, no. 7762, pp. 504–508, Jun. 2019, doi: 10.1038/s41586-019-1260-x.

[43] L. Liu, S. Chen, M. Li, K. Li, and F. Wang, 'Enhanced Ammonia Synthesis via Plasma-Assisted Catalysis: Insights Into CoNi Bimetallic Systems on SBA-15 Supports', *ChemSusChem*, vol. 19, no. 1, p. e202501834, Jan. 2026, doi: 10.1002/cssc.202501834.

[44] Z. Han, Q. Xue, X. Hu, T. Guo, J. Ma, and Q. Guo, 'A Comprehensive Review of Chemical Looping Ammonia Synthesis', *Innov. Discov.*, vol. 1, no. 2, p. 9, May 2024, doi: 10.53964/id.2024009.

[45] F. Han *et al.*, 'Towards Sustainable Industry: A Comprehensive Review of Energy–Economy–Environment System Analysis and Future Trends', *Sustainability*, vol. 16, no. 12, p. 5085, Jan. 2024, doi: 10.3390/su16125085.

[46] Y. Cao, N. Zhang, X. Zhang, J. Bao, and G. He, '4E analysis of ammonia production scenarios with different hydrogen production technologies', *Int. J. Hydrog. Energy*, vol. 102, pp. 360–374, 2025, doi: 10.1016/j.ijhydene.2025.01.005.

[47] G. A. Cuevas-Castillo, S. Michailos, K. Hughes, D. Ingham, and M. Pourkashanian, 'A comprehensive process modelling, techno-economic and life cycle assessment of a power to ammonia process', *Sustain. Energy Technol. Assess.*, vol. 76, 2025, doi: 10.1016/j.seta.2025.104278.

[48] M. Chahrour, C. Wulf, and P. Zapp, 'Assessing climate change impact of blue ammonia via carbon capture and utilization in life cycle modelling', *J. Environ. Manage.*, vol. 383, 2025, doi: 10.1016/j.jenvman.2025.125438.

[49] M. Tjahjono, I. Stevani, G. A. Siswanto, A. Adhitya, and I. Halim, 'Assessing the feasibility of gray, blue, and green ammonia productions in Indonesia: A techno-economic and environmental perspective', *Int. J. Renew. Energy Dev.*, vol. 12, no. 6, pp. 1030–1040, 2023, doi: 10.14710/ijred.2023.58035.

[50] P. Mayer *et al.*, 'Blue and green ammonia production: A techno-economic and life cycle assessment perspective', *iScience*, vol. 26, no. 8, 2023, doi: 10.1016/j.isci.2023.107389.

[51] Y. Bicer, I. Dincer, C. Zamfirescu, G. Vezina, and F. Raso, 'Comparative life cycle assessment of various ammonia production methods', *J. Clean. Prod.*, vol. 135, pp. 1379–1395, 2016, doi: 10.1016/j.jclepro.2016.07.023.

[52] A. O. Oni, T. Giwa, C. Font-Palma, and D. A. Fadare, 'Comparative techno-economic and life cycle greenhouse gas assessment of ammonia production from thermal decomposition of methane and steam methane reforming technologies', *Int. J. Greenh. Gas Control*, vol. 123, p. 103819, Feb. 2023, doi: 10.1016/j.ijggc.2022.103819.

[53] L. Al-Ghussain, M. Alrbai, and S. Al-Dahidi, 'Comprehensive techno-economic and life cycle greenhouse gases analysis of green ammonia production utilizing PV and wind energy: Jordan as a case study', *Renew. Energy*, vol. 249, p. 123249, Aug. 2025, doi: 10.1016/j.renene.2025.123249.

[54] A. M. O. Mohamed and Y. Bicer, 'Coupling of a novel boron-based thermochemical cycle with chemical looping combustion to produce ammonia and power', *Int. J. Hydrog. Energy*, vol. 46, no. 57, pp. 28949–28960, Aug. 2021, doi: 10.1016/j.ijhydene.2020.11.182.

[55] D.-A. Chisalita, L. Petrescu, and C.-C. Cormos, 'Environmental evaluation of european ammonia production considering various hydrogen supply chains', *Renew. Sustain. Energy Rev.*, vol. 130, 2020, doi: 10.1016/j.rser.2020.109964.

[56] A.J. Boero *et al.*, 'Environmental life cycle assessment of ammonia-based electricity', *Energies*, vol. 14, no. 20, 2021, doi: 10.3390/en14206721.

[57] Y. Bicer, I. Dincer, G. Vezina, and F. Raso, 'Impact Assessment and Environmental Evaluation of Various Ammonia Production Processes', *Environ. Manage.*, vol. 59, no. 5, pp. 842–855, 2017, doi: 10.1007/s00267-017-0831-6.

[58] K. Ren *et al.*, 'Life cycle assessment of ammonia synthesis based on pulverized coal entrained flow gasification technology in China', *J. Clean. Prod.*, vol. 328, 2021, doi: 10.1016/j.jclepro.2021.129658.

[59] A. M. O. Mohamed, S. G. Al-Ghamdi, and Y. Bicer, 'Life cycle assessment of clean ammonia synthesis from thermo-catalytic solar cracking of liquefied natural gas', *Int. J. Hydrog. Energy*, vol. 46, no. 77, pp. 38551–38562, 2021, doi: 10.1016/j.ijhydene.2021.09.080.

[60] Y. Bicer and I. Dincer, 'Life cycle assessment of nuclear-based hydrogen and ammonia production options: A comparative evaluation', *Int. J. Hydrog. Energy*, vol. 42, no. 33, pp. 21559–21570, 2017, doi: 10.1016/j.ijhydene.2017.02.002.

[61] P. Arora, I. Sharma, A. Hoadley, S. Mahajani, and A. Ganesh, 'Remote, small-scale, "greener" routes of ammonia production', *J. Clean. Prod.*, vol. 199, pp. 177–192, Oct. 2018, doi: 10.1016/j.jclepro.2018.06.130.

[62] S. Vinardell, P. Nicolas, A. M. Sastre, J. L. Cortina, and C. Valderrama, 'Sustainability Assessment of Green Ammonia Production To Promote Industrial Decarbonization in Spain', *ACS Sustain. Chem. Eng.*, vol. 11, no. 44, pp. 15975–15983, 2023, doi: 10.1021/acssuschemeng.3c04694.

[63] G. Song *et al.*, 'Techno-economic and life cycle greenhouse gas assessment of green ammonia produced by low-pressure Haber-Bosch process', *Energy Nexus*, vol. 17, 2025, doi: 10.1016/j.nexus.2025.100379.

[64] N. Campion, H. Nami, P. R. Swisher, P. Vang Hendriksen, and M. Münster, 'Techno-economic assessment of green ammonia production with different wind and solar potentials', *Renew. Sustain. Energy Rev.*, vol. 173, 2023, doi: 10.1016/j.rser.2022.113057.

[65] S. Oh, H. Mun, J. Park, and I. Lee, 'Techno-economic comparison of ammonia production processes under various carbon tax scenarios for the economic transition from grey to blue ammonia', *J. Clean. Prod.*, vol. 434, 2024, doi: 10.1016/j.jclepro.2023.139909.

[66] K. Lee, X. Liu, P. Vyawahare, P. Sun, A. Elgowainy, and M. Wang, 'Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production', *Green Chem.*, vol. 24, no. 12, pp. 4830–4844, 2022, doi: 10.1039/d2gc00843b.

[67] S. Sahu *et al.*, 'Techno-enviro-economic evaluation of decentralized solar ammonia production plant in India under various energy supply scenarios', *Energy Convers. Manag.*, vol. 318, p. 118908, Oct. 2024, doi: 10.1016/j.enconman.2024.118908.

[68] J. Osorio-Tejada, N. N. Tran, and V. Hessel, 'Techno-environmental assessment of small-scale Haber-Bosch and plasma-assisted ammonia supply chains', *Sci. Total Environ.*, vol. 826, 2022, doi: 10.1016/j.scitotenv.2022.154162.

[69] M. U. Sajid and Y. Bicer, 'Thermodynamic assessment of chemical looping combustion and solar thermal methane cracking-based integrated system for green ammonia production', *Therm. Sci. Eng. Prog.*, vol. 19, 2020, doi: 10.1016/j.tsep.2020.100588.

[70] A. Isella, R. Ostuni, and D. Manca, 'Towards the decarbonization of ammonia synthesis – A techno-economic assessment of hybrid-green process alternatives', *Chem. Eng. J.*, vol. 486, 2024, doi: 10.1016/j.cej.2024.150132.

[71] M. Moosazadeh, A. Mansourimarand, S. Ajori, V. Taghikhani, and C. Yoo, 'Waste-to-Ammonia: A sustainable pathway for energy transition', *Renew. Sustain. Energy Rev.*, vol. 208, 2025, doi: 10.1016/j.rser.2024.115012.

[72] 'Hydrogen for power generation'.

[73] 'Microsoft Word - Documentation for Coal Information (2019 edition)_v00_FINAL.docx'. Accessed: Nov. 02, 2025. [Online]. Available: https://iea.blob.core.windows.net/assets/c12711c4-3fb1-4449-9ea6-10815c832a36/Coal_Documentation.pdf?utm_source=chatgpt.com

[74] '2017-26-The-revision-of-ISO-6976-and-assessment-of-the-impacts-of-changes-Lander-Dave-Lander-Consulting.pdf'. Accessed: Nov. 02, 2025. [Online]. Available: https://nfogm.no/wp-content/uploads/2019/02/2017-26-The-revision-of-ISO-6976-and-assessment-of-the-impacts-of-changes-Lander-Dave-Lander-Consulting.pdf?utm_source=chatgpt.com

[75] 'imfname_11207195.pdf'. Accessed: Oct. 27, 2025. [Online]. Available: https://www.parlament.gv.at/dokument/XXVII/EU/126576/imfname_11207195.pdf?

[76] 'Microsoft Word - E02_gas_fired_power_FINAL_Apr_2010_GS_OK_ADfinal.doc'. Accessed: Oct. 27, 2025. [Online]. Available: https://iea-etsap.org/E-TechDS/PDF/E02-gas_fired_power-GS-AD-gct.pdf

[77] "https://www.consilium.europa.eu/en/infographics/how-is-eu-electricity-produced-and-sold/?," [Online].

[78] "https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics," [Online].

[79] "https://www.iea.org/statistics-questionnaires-faq," [Online].

[80] "https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/d7bt/mm23," [Online].

[81] "https://www.bls.gov/cpi/tables/supplemental-files/," [Online].

[82] "https://ec.europa.eu/eurostat/web/hicp/database," [Online].

[83] "https://data.ecb.europa.eu/data/datasets/EXR/EXR.M.GBP.EUR.SP00.A," [Online].

[84] "https://data.ecb.europa.eu/data/datasets/EXR/EXR.M.USD.EUR.SP00.A," [Online].

[85] annela, "https://elenger.ee/en/gas-market-overview-q1-2025/," [Online].

[86] 'PowerPoint Presentation'. Accessed: Oct. 27, 2025. [Online]. Available: https://open.overheid.nl/documenten/e6b7b594-c0a4-44c3-8546-788bdc9cd68e/file

[87] O. US EPA, "https://www.epa.gov/ghgemissions/understanding-global-warming-potentials," [Online].

[88] "https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html," [Online].

[89] "https://ammoniaenergy.org/articles/establishing-ammonia-import-bases-in-singapore-south-korea-and-japan/," [Online].

[90] M. Al-Breiki and Y. Bicer, *Sustainable Energy Carriers for Energy Storage and Transport: Exploring Advanced Solutions for a Green Future*. in Green Energy and Technology. Cham: Springer Nature Switzerland, 2025. doi: 10.1007/978-3-031-91615-1.

[91] 'Guidance_for_inspection_of_atmospheric__refrigerated_ammonia_storage_tanksVJ_website'.

[92] 'hydrogen-factsheet-ammonia'.

[93] 'csb_eprs_alert.pdf'. Accessed: Feb. 17, 2026. [Online]. Available: https://www.csb.gov/assets/1/6/csb_eprs_alert.pdf

[94] 'Dealing with an Ammonia Spill'.

[95] S. Nand, M. Goswami, and A. Jain, 'The Fertiliser Association of India, FAI house, 10 Shaheed Jit Singh Marg, New Delhi'.

[96] R. M. Nayak-Luke, C. Forbes, Z. Cesaro, R. Bañares-Alcántara, and K. H. R. Rouwenhorst, 'Techno-Economic Aspects of Production, Storage and Distribution of Ammonia', in *Techno-Economic Challenges of Green Ammonia as an Energy Vector*, Elsevier, 2021, pp. 191–207. doi: 10.1016/B978-0-12-820560-0.00008-4.

[97] B. McCriddle, "https://www.gosships.com/post/ammonia-as-a-marine-fuel-and-ammonia-carriers-technology-fleet-and-2030-outlook," [Online].

[98] Y. Seo *et al.*, 'Technical–Economic Analysis for Ammonia Ocean Transportation Using an Ammonia-Fueled Carrier', *Sustainability*, vol. 16, no. 2, p. 827, Jan. 2024, doi: 10.3390/su16020827.

[99] 'h2uppp-ppp-result-india-rwe-en'.

[100] "https://www.wartsila.com/encyclopedia/term/gas-carrier-types," [Online].

[101] 'sigtto-2024-gas-as-fuel-on-gas-carriers'.

[102] "https://www.dnv.com/expert-story/maritime-impact/investing-in-future-ammonia-markets/," [Online].

[103] G. MacGuire and B. White, *Liquefied gas handling principles: on ships and in terminals*, 3. ed. London: Witherby, 2000.

[104] 'Transcaer'.

[105] 'Guidance_for_transporting_ammonia_in_rail_4'.

[106] '2025-ISPT-Ammonia-Pipeline-report_versie-2.0'.

[107] ‘Guidance_for_inspection_of_and_leak_detection_in_liquid_ammonia_pipelines_FINAL_01’.

[108] ‘ammonia-bunkering-advisory’.

[109] ‘FertilizerCanada_2022-Ammonia-Code_Version-1.2May-2024_FINAL-1’.

[110] ‘sigtto-2021-esd-systems’.

[111] "https://www.imo.org/en/ourwork/safety/pages/igc-code.aspx," [Online].

[112] "https://www.imo.org/en/ourwork/safety/pages/dangerousgoods-default.aspx," [Online].

[113] ‘2000-OPRC-HNS’.

[114] *Directive 2008/68/EC of the European Parliament and of the Council of 24 September 2008 on the inland transport of dangerous goods (Text with EEA relevance)*, vol. 260. 2008. Accessed: Feb. 14, 2026. [Online]. Available: http://data.europa.eu/eli/dir/2008/68/oj

[115] "https://eur-lex.europa.eu/eli/dir/2012/18/oj/eng," [Online].

[116] *Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment (recast) Text with EEA relevance*, vol. 189. 2014. Accessed: Feb. 14, 2026. [Online]. Available: http://data.europa.eu/eli/dir/2014/68/oj

[117] *Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (recast) (Text with EEA relevance)*, vol. 334. 2010. Accessed: Feb. 14, 2026. [Online]. Available: http://data.europa.eu/eli/dir/2010/75/oj

[118] *Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on classification, labelling and packaging of substances and mixtures, amending and repealing Directives 67/548/EEC and 1999/45/EC, and amending Regulation (EC) No 1907/2006 (Text with EEA relevance)*, vol. 353. 2008. Accessed: Feb. 14, 2026. [Online]. Available: http://data.europa.eu/eli/reg/2008/1272/oj

[119] ‘CFR-2024-title29-vol5-sec1910-111’.

[120] "https://www.ecfr.gov/current/title-40/part-68," [Online].

[121] ‘CFR-2018-title49-vol2-sec172-101’.

[122] "https://www.japaneselawtranslation.go.jp/en/laws/view/4754/en," [Online].

[123] ‘High-Pressure Gas Safety Control Act_12.12.1996’.

[124] ‘Singapore-WHS_Major_Hazard_Installations_Regulations2017’.

[125] "https://www.nea.gov.sg/our-services/pollution-control/chemical-safety/hazardous-substances/management-of-hazardous-substances," [Online].

[126] "https://single-market-economy.ec.europa.eu/single-market/goods/european-standards/harmonised-standards_en," [Online].

[127] "https://www.iso.org/standard/41079.html," [Online].

[128] "https://www.asme.org/codes-standards/bpvc-standards," [Online].

[129] ‘AEA-LEAD-Vessels-Executive-Summary-September-2025’.

[130] "https://www.mitsui.com/jp/en/release/2025/1251204_14855.html," [Online].

[131] "https://www.cip.com/projects/our-projects/st-charles/," [Online].

[132] "https://www.opportunitylouisiana.gov/news/st-charles-clean-fuels-proposes-4-6-billion-reduced-carbon-ammonia-facility-in-st-rose," [Online].

[133] "https://investors.navigatorgas.com/press-releases/news-details/2024/Navigator-Gas-and-Attis-Clean-Energy-Invest-In-Ten08-Energy-To-Produce-Clean-Ammonia-on-the-US-Gulf-Coast-for-Export/default.aspx," [Online].

[134] '2023-02-08-rwe-lotte-mc-enter-into-jsa-to-develop-clean-ammonia-project.pdf'. Accessed: Feb. 18, 2026. [Online]. Available: https://www.rwe.com/-/media/RWE/documents/07-presse/rwe-supply-and-trading/2023/2023-02-08-rwe-lotte-mc-enter-into-jsa-to-develop-clean-ammonia-project.pdf

[135] "https://ir.cfindustries.com/Investors/news/news-details/2025/CF-Industries-Announces-Joint-Venture-with-JERA-Co--Inc--and-Mitsui--Co--Inc--for-Production-and-Offtake-of-Low-Carbon-Ammonia/default.aspx," [Online].

[136] "https://www.vopak.com/newsroom/news/gasunie-hes-international-and-vopak-join-forces-develop-import-terminal-hydrogen?language_content_entity=en," [Online].

[137] "https://cinea.ec.europa.eu/news-events/news/cef-energy-eu650-million-allocated-14-cross-border-energy-infrastructure-projects-2026-01-28_en," [Online].

[138] "https://www.fluxys.com/en/projects/ammonia-antwerp-terminal," [Online].

[139] "https://www.uniper.energy/about-uniper/projects/energy-transformation-hub-northwest/green-wilhelmshaven," [Online].

[140] 'PCIFiche_9.11.3_1st_PCI_PMI_list.pdf'. Accessed: Feb. 14, 2026. [Online]. Available: https://ec.europa.eu/assets/cinea/PCI/files/PCIFiche_9.11.3_1st_PCI_PMI_list.pdf

[141] '2022-03-18-import-of-green-enery-rwe-builds-ammonia-terminal-in-brunsbuettel.pdf'. Accessed: Feb. 18, 2026. [Online]. Available: https://www.rwe.com/-/media/RWE/documents/07-presse/rwe-ag/2022/2022-03-18-import-of-green-enery-rwe-builds-ammonia-terminal-in-brunsbuettel.pdf

[142] "https://www.mitsubishicorp.com/jp/en/news/release/2023/0000051095.html," [Online].

[143] "https://www.tokuyama.co.jp/eng/news/2022/2022083001.html," [Online].

[144] "https://news.samsungcnt.com/en/features/engineering-construction/2024-07-samsung-cnt-is-building-koreas-first-ammonia-import-terminal-for-co-firing-power-generation/," [Online].

[145] "https://ammoniaenergy.org/articles/hyundai-ulsan-city-to-establish-koreas-first-mega-scale-ammonia-import-facility/," [Online].

[146] 'joint-media-release---consortium-appointed-for-next-phase-of-study-on-low--or-zero-carbon-ammonia.pdf'. Accessed: Feb. 18, 2026. [Online]. Available: https://www.mpa.gov.sg/docs/mpalibraries/circulars-and-notices/joint-media-release---consortium-appointed-for-next-phase-of-study-on-low--or-zero-carbon-ammonia.pdf?sfvrsn=88f5396c_1

[147] "https://www.drewry.co.uk/maritime-research-opinion-browser/maritime-research-opinions/ammonia-shipborne-trade-navigating-the-bubble-for-sustainable-growth," [Online].

[148] "https://ammoniaenergy.org/articles/ammonia-pipelines-existing-networks-future-deployments-and-safety-considerations/," [Online].

[149] 'Explainer: Why would pipeline damage threaten Black Sea grain deal?', *Reuters*, Jun. 07, 2023. Accessed: Feb. 15, 2026. [Online]. Available: https://www.reuters.com/world/europe/why-would-pipeline-damage-threaten-black-sea-grain-deal-2023-06-07/

[150] B. Bonnet-Cantalloube, M. Espitalier-Noël, P. F. de Carvalho, J. Fonseca, and G. Pawelec, 'Photo Cover © Justin Jin for Hydrogen Europe'.

[151] 'CIEP-Europe'.

[152] P. S.-L. Chen *et al.*, 'Opportunities and Challenges of Hydrogen Ports: An Empirical Study in Australia and Japan', *Hydrogen*, vol. 5, no. 3, pp. 436–458, Jul. 2024, doi: 10.3390/hydrogen5030025.

[153] N. Souissi, *Fueling the future: practical considerations for low-carbon ammonia adoption in the maritime sector*. in OIES paper ET, no. 49. Oxford: The Oxford Institute for Energy Studies, 2025.

[154] *Safety and operational guidelines for piloting ammonia bunkering in Singapore*. Singapore: Global Centre for Maritime Decarbonisation, 2023.

[155] T. Kuchta, A. Wróblewska, J. Holewa-Rataj, and A. Król, 'Threats and Challenges Associated with Ammonia Transport via Pipeline Systems', *Appl. Sci.*, vol. 15, no. 21, p. 11465, Oct. 2025, doi: 10.3390/app152111465.

A Detailed description of environmental dimension

Table A.1 - LCA based impact indicators description and main drivers. FU=1 t of ammonia.

LCA Impact Indicator	Description	Main drivers
A **[mol H^+_{eq}]**	Acidification, expressed as an equivalent amount of proton load (H^+).	Emissions of acidifying precursors (SO_2, NO_x, NH_3) and their atmospheric transformation and deposition.
ALO **[m^2·a]**	Agricultural Land Occupation, expressed as area-time.	Crop production requirements, yields, and agricultural management practices.
AP **[kg SO_{2eq}]**	Acidification Potential, tendency of emissions to increase acidity in terrestrial and aquatic environments, expressed as equivalent amount of SO_2.	SO_2, NO_x and NH_3 emissions (combustion, industrial processes, agriculture) and their atmospheric deposition patterns.
C **[cases]**	Carcinogens (human health impact indicator) expressed as the expected number of attributable cases in the exposed population.	Emissions of carcinogenic pollutants, exposure pathways, and characterisation factors linking exposure to health effects.
EP **[kg PO_{4eq}]**	Eutrophication Potential expressed as equivalent amount of phosphate (PO_4).	Releases of nutrients (P and N) to water/soil, influenced by wastewater management and agricultural runoff.
EQ **[species·year]**	Ecosystem Quality expressed as species loss over time.	Land occupation and transformation, habitat disturbance, and emissions affecting ecosystem integrity.
ER non-REN **[MJ]**	Energy Resources (non-renewable), representing the primary energy use over the life cycle, expressed in MJ.	Consumption of non-renewable energy carriers across the life cycle, including production, transport, and end-of-life stages.

LCA Impact Indicator	Description	Main drivers
FAETP [kg 1,4-Db$_{eq}$]	Freshwater Aquatic Ecotoxicity Potential expressed as equivalent amount of 1,4-dichlorobenzene (1,4-Db).	Chemical emissions to freshwater ecosystems, environmental fate and exposure, and ecotoxicity characterisation factors.
FDP [kg oil$_{eq}$]	Fossil Depletion Potential, expressed as equivalent amount of oil.	Consumption of fossil energy carriers (oil, gas, coal) across all life-cycle stages.
FEP [kg PO_{4eq}]	Freshwater Eutrophication Potential expressed as equivalent amount of phosphate (PO_4).	Nutrient discharges to freshwater, especially phosphorus compounds.
FETP [kg 1,4-Db$_{eq}$]	Freshwater Ecotoxicity Potential expressed as equivalent amount of 1,4-dichlorobenzene (1,4-Db).	Chemical emissions, environmental fate and exposure, and ecotoxicity characterisation factors.
FETP [CTU$_e$]	Freshwater Ecotoxicity Potential expressed in comparative toxic units for ecosystems (CTUe).	Chemical emissions, environmental fate and exposure, and ecotoxicity characterisation factors.
FETP [PAF·m^3·d]	Freshwater Ecotoxicity Potential expressed as Potentially Affected Fraction (PAF) over volume and time (m^3·d).	Chemical emissions to freshwater, their persistence and distribution in the environment, and ecosystem sensitivity to exposure.
FRS [kg oil$_{eq}$]	Fossil Resource Scarcity, expressed as equivalent amount of oil.	Dependence on finite fossil reserves and extraction intensity driven by energy demand.
GWP_{500} [t CO_2]	Global Warming Potential over 500-year time horizon, expressed as equivalent amount of CO_2.	Long-lived greenhouse gas emissions, primarily CO_2, and to a lesser extent CH_4 and N_2O.
HH [DALY]	Human Health damage expressed in Disability-Adjusted Life Years (DALY).	Pollutant emissions, exposure pathways, and effect factors contributing to chronic and acute health impacts.

LCA Impact Indicator	Description	Main drivers
HT c [CTUh]	Human Toxicity (cancer effects) expressed in comparative toxic units for humans (CTUh).	Emissions of carcinogenic substances, exposure pathways, and human health characterisation factors.
HT nc [CTUh]	Human Toxicity (non-cancer effects), expressed in comparative toxic units for humans (CTUh).	Emissions of non-carcinogenic substances, exposure pathways, and human health characterisation factors.
HTP_{500} [kg 1,4-Db_{eq}]	Human Toxicity Potential over a 500-year time horizon, expressed as equivalent amount of 1,4-dichlorobenzene (1,4-Db).	Chemical emissions, long-term environmental fate, exposure pathways, and human health characterisation factors.
IR [Bq C_{14eq}]	Ionising Radiation expressed as an equivalent amount of radioactivity of carbon-14 in Becquerels (Bq C_{14}).	Radioactive releases across the life cycle and their environmental dispersion and exposure pathways.
IRP [kg U_{235eq}]	Ionising Radiation Potential related to radionuclide emissions and/or nuclear fuel cycle processes., expressed as equivalent amount of U_{235}.	Nuclear fuel cycle activities, radioactive emissions, and associated exposure pathways.
LO [ha.y]	Arable Land Occupation, expressed as arable hectares-years.	Duration and intensity of arable land use driven by feedstock and material demand.
LU [m^2·a $crop_{eq}$]	Land Use expressed as amount of crop-equivalent area-time.	Type of crop, yield factors and land occupation throughout the supply chain.
MAETP [kg 1,4-Db_{eq}]	Marine Aquatic Ecotoxicity Potential expressed as equivalent amount of 1,4-dichlorobenzene (1,4-Db).	Chemical emissions to marine ecosystems, environmental fate and dispersion, and ecotoxicity characterisation factors.
MDP [kg Fe_{eq}]	Metal Depletion Potential expressed as equivalent amount of iron (Fe).	Use of metal resources across the life cycle, influenced by material demand, metal content, and resource extraction.
MEP [kg N_{eq}]	Marine Eutrophication Potential, expressed as equivalent amount of nitrogen (N).	Nitrogen emissions to marine waters via riverine transport, wastewater and agricultural pathways.

LCA Impact Indicator	Description	Main drivers
MR (m/m) [g Sb_{eq}]	Material Resource depletion (minerals/metals), expressed as equivalent amount of antimony (Sb).	Use of non-renewable materials, influenced by material selection, mass intensity and recovery at end-of-life.
MRS [kg Cu_{eq}]	Mineral Resource Scarcity expressed as equivalent amount of copper (Cu).	Demand for scarce minerals/metals, ore grades, extraction intensity and recycling availability.
NC [cases]	Non-Carcinogens (human health impact indicator) expressed as the expected number of attributable cases in the exposed population.	Emissions of non-carcinogenic pollutants, exposure pathways, and characterisation factors linking exposure to health effects.
NLT [m^2]	Natural Land Transformation, expressed as converted area.	Land-use change and conversion of natural habitats due to infrastructure and resource extraction.
OF (eco) [kg NO_{xeq}]	Ozone Formation potential relevant to ecosystems, expressed as equivalent amount of NO_x.	NO_x emissions and photochemical regimes affecting ozone levels and vegetation exposure.
OF (hum) [kg NO_{xeq}]	Ozone Formation potential relevant to human health, expressed as equivalent amount of NO_x.	NO_x and VOC emissions, atmospheric reactivity, and conditions favouring ozone production.
PF [kg $PM2.5_{eq}$]	Particulate Formation, expressed as equivalent amount of PM2.5.	Fine particulate emissions and secondary aerosol precursors (SO_2, NO_x, NH_3), mainly from combustion and traffic.
PF [kg PM_{10eq}]	Particulate Formation, expressed as equivalent amount of PM10.	Dust and mechanically generated particles, as well as combustion-related emissions.
PMF [disease incidence]	Particulate Matter Formation, health burden due to particulate matter exposure, expressed as disease incidence.	Primary and secondary particulate matter emissions, population exposure, and health effect characterisation factors.
POFP [kg $NMVOC_{eq}$]	Photochemical Ozone Formation Potential, expressed as equivalent amount of non-methane volatile organic compounds (NMVOC).	Emissions of ozone precursors (NMVOCs and NO_x) under sunlight; influenced by atmospheric chemistry.

LCA Impact Indicator	Description	Main drivers
POFP (human health) [kg $NMVOC_{eq}$]	Photochemical Ozone Formation Potential with a focus on human health effects, expressed as equivalent amount of non-methane volatile organic compounds (NMVOC).	NMVOC and NO_x emissions and the resulting tropospheric ozone formation affecting exposure.
POP [kg C_2H_{4eq}]	Photochemical Ozone formation Potential, expressed as equivalent amount of ethene (C_2H_4).	Emissions of VOCs and NO_x driving oxidant formation under photochemical conditions.
R [$]	Resources, economic indicator representing life-cycle cost or value, expressed in monetary terms.	Costs associated with materials, energy, labour, logistics, and process-specific expenditures across the supply chain.
TEP [mol N_{eq}]	Terrestrial Eutrophication Potential, expressed as equivalent amount of nitrogen (N).	Atmospheric nitrogen emissions (NO_x, NH_3) and subsequent deposition to terrestrial ecosystems.
TETP [kg 1,4-DB_{eq}]	Terrestrial Ecotoxicity Potential expressed as equivalent amount of 1,4-dichlorobenzene (1,4-Db).	Chemical emissions to soil and land, environmental fate and exposure, and ecotoxicity characterisation factors.
ULO [$m^2 \cdot a$]	Urban/industrial Land Occupation, expressed as area-time.	Built infrastructure footprint and duration of land occupation.
WC [m^3]	Water Consumption, expressed as net freshwater use in cubic meters.	Net withdrawals minus returns, influenced by process water demand and local hydrological context.
WD [m^3_{eq}]	Water Depletion expressed as an equivalent amount of affected volume in cubic meters.	Freshwater withdrawals and consumption, influenced by process water demand and local water availability/scarcity conditions.
WU [m^3 $world_{eq}$]	Water Use weighted by regional scarcity factor, expressed as world-equivalent cubic metres.	Geographical water stress factors combined with local water withdrawals.

Table A. 2 - Occurrence matrix of LCA impact indicators reported in the reviewed literature, for each conventional ammonia production pathway.

LCA Impact Indicator		Brown	Grey	Blue	Turquoise	Pink	Green	Yellow	LCA Impact Category
A [mol H^+_{eq}]	Acidification	0	0	1	0	0	1	0	Terrestrial/Freshwater Acidification
ALO [m^2a]	Agricultural Land Occupation	1	1	0	0	0	1	0	Land Use
AP [kg SO_{2eq}]	Acidification Potential	0	1	0	1	5	1	0	Terrestrial/Freshwater Acidification
C [cases]	Carcinogens	2	1	1	0	0	1	1	Human Health
EP [kg PO_{4eq}]	Eutrophication Potential	0	0	0	0	0	1	0	Eutrophication (Generic)
EQ [species·year]	Ecosystem Quality	2	0	0	0	0	0	0	Ecosystem Quality
ER non-REN [MJ]	Energy Resources non-Renewable	0	0	1	0	0	1	0	Non-Renewable Energy Use
FAETP [kg 1,4-Db_{eq}]	Freshwater Aquatic EcoToxicity Potential	0	0	0	0	0	1	0	Freshwater Ecotoxicity
FDP [kg oil_{eq}]	Fossil Depletion Potential	3	4	4	1	1	10	2	Fossil Resource Use / Energy Use
FEP [kg P_{eq}]	Freshwater Eutrophication Potential	0	3	3	1	1	11	1	Freshwater Eutrophication
FEP [kg PO_{4eq}]	Freshwater Eutrophication Potential	3	2	2	0	0	3	1	Freshwater Eutrophication
FETP [kg 1,4-Db_{eq}]	Freshwater EcoToxicity Potential	1	1	2	1	0	2	1	Freshwater Ecotoxicity
FETP [CTU_{eq}]	Freshwater EcoToxicity Potential	0	0	1	0	0	1	0	Freshwater Ecotoxicity
FETP [PAF.m^3.d]	Freshwater EcoToxicity Potential	2	1	1	0	0	1	1	Freshwater Ecotoxicity

LCA Impact Indicator		Brown	Grey	Blue	Turquoise	Pink	Green	Yellow	LCA Impact Category
FRS [kg oil_{eq}]	Fossil Resource Scarcity	0	1	0	0	0	3	0	Fossil Resource Use / Energy Use
GWP_{500} [t CO_{2eq}]	Global Warming Potential over 500 years	2	3	1	0	11	3	3	Climate Change
HH [DALY]	Human Health	2	0	0	0	0	0	0	Human Health
HT c [CTUh]	Human Toxicity (carcinogens)	0	0	1	0	0	1	0	Human Toxicity – Carcinogenic
HT nc [CTUh]	Human Toxicity (non-carcinogens)	0	0	1	0	0	1	0	Human Toxicity – Non-Carcinogenic
HTP_{500} [kg 1,4-Db_{eq}]	Human Toxicity Potential over 500 years	2	2	1	0	6	3	3	Human Toxicity (Total)
IR [Bq C_{14eq}]	Ionizing Radiation	2	1	1	0	0	1	1	Ionising Radiation
IRP [kg U_{235eq}]	Ionising Radiation Potential	1	3	1	0	1	8	0	Ionising Radiation
LO [ha.y arable]	Land Occupation	2	1	1	0	0	1	1	Land Use
LU [m^2a crop $_{eq}$]	Land Use	0	1	0	0	0	3	0	Land Use
MAETP [kg 1,4-Db_{eq}]	Marine Aquatic EcoToxicity Potential	1	1	0	0	0	2	0	Marine Ecotoxicity
MDP [kg Fe_{eq}]	Mineral Depletion Potential	3	2	3	1	0	3	2	Metal Resource Depletion
MEP [kg N_{eq}]	Marine Eutrophication Potential	3	2	2	0	0	3	1	Marine Eutrophication
MR (m/m) [g Sb_{eq}]	Material Resource (minerals/metals)	0	0	1	0	0	1	0	Mineral Resource Depletion
MRS [kg Cu_{eq}]	Mineral Resource Scarcity	0	1	0	2	0	3	0	Metal Resource Scarcity
NC [cases]	Non-Carcinogens	2	1	1	0	0	1	1	Human Health
NLT [m^2]	Natural Land Transformation	1	1	0	0	0	1	0	Land Use

LCA Impact Indicator		Brown	Grey	Blue	Turquoise	Pink	Green	Yellow	LCA Impact Category
OF (eco) [kg NO_x]	Ozone Formation (ecosystem)	2	1	1	0	0	1	1	Photochemical Ozone Formation
OF (hum) [kg NO_x]	Ozone Formation (human)	2	1	1	1	0	1	1	Photochemical Ozone Formation
PF [kg $PM2.5_{eq}$]	Particulate Formation	2	1	1	2	0	1	1	Particulate Matter – Human Health
PF [kg $PM10_{eq}$]	Particulate Formation	1	1	0	0	0	1	0	Particulate Matter – Human Health
PMF [disease incidence]	Particulate Matter Formation	0	0	1	0	0	1	0	Particulate Matter – Human Health
POFP [kg $NMVOC_{eq}$]	Photochemical Ozone Formation Potential	1	3	3	1	1	9	1	Photochemical Ozone Formation
POFP (human health) [kg $NMVOC_{eq}$]	Photochemical Ozone Formation Potential	0	0	1	0	0	1	0	Photochemical Ozone Formation
POP [kg C_2H_{4eq}]	Photochemical Ozone Potential	0	0	0	0	0	1	0	Photochemical Ozone Formation
R [$]	Resources	2	0	0	0	0	0	0	Cost/Economic Impact
TEP [mol N_{eq}]	Terrestrial Eutrophication Potential	0	0	1	0	0	1	0	Terrestrial Eutrophication
TETP [kg 1,4-DB_{eq}]	Terrestrial EcoToxicity Potential	1	2	2	1	5	3	1	Terrestrial Ecotoxicity
ULO [m^2a]	Urban Land Occupation	1	1	0	0	0	1	0	Land Use
WC [m^3]	Water Consumption	0	0	0	0	0	1	0	Water Use/Consumption
WD [m^3_{eq}]	Water Depletion	3	2	1	0	0	2	1	Water Use/Consumption
WU [m^3 world $_{eq}$]	Water Use	0	0	1	0	0	1	0	Water Use/Consumption

B Methodology for global ammonia infrastructure requirements

This appendix documents the calculation framework used to estimate global infrastructure requirements for ammonia across three segments: port/industrial storage, seaborne and pipeline transport. Results are produced for 2030 and 2050 under two IRENA scenarios (1.5°C and Stated Policies) and are intended for scale-up comparisons with a 2024 baseline. Storage is expressed as a capacity stock (Mt), while seaborne and pipeline metrics represent annual throughput (Mt/y).

B.1 Scope and outputs

The scope is to estimate the following global quantities, starting from demand projections for the different scenarios:

- Required port/industrial storage capacity [Mt];
- Required seaborne throughput [Mt/y];
- Required pipeline throughput [Mt/y].

All outputs include both existing markets (fertilisers and other established industrial uses) and new uses (shipping fuel, hydrogen carrier and power generation). Total requirements are computed as the sum of an existing-market component and a new-use component.

B.2 Notation

Each variable is labelled by a superscript s (‘1.5’ or ‘SP’) indicating the IRENA’s scenario, and a subscript t for the considered deadline (‘2030’ or ‘2050’).

Demand variables:

- $D^{s}_{exist,t}$: ammonia demand for existing markets [Mt/y];
- $D^{s}_{new,t}$: ammonia demand for new uses [Mt/y].

Infrastructure variables:

- S_t^s: required port/industrial storage capacity [Mt];
- $T_{sea,t}^s$: required seaborne throughput [Mt/y];
- $T_{pipe,t}^s$: required pipeline throughput [Mt/y].

B.3 Input data and baseline proxies

B.3.1 Demand inputs from IRENA

New-use demand is computed according to Equation (22):

$$D_{new,t}^s = D_{shipfuel,t}^s + D_{carrier,t}^s + D_{power,t}^s \left[\frac{Mt}{y}\right] \quad (22)$$

for 2030, the power-generation component is reported by IRENA as a Japan-only range; therefore $D_{new,2030}^s$ (and any derived infrastructure outputs for 2030 that depend on it) are reported as low/high ranges [9]. Existing-market demand values are taken directly from IRENA and, in the present implementation, are treated as scenario-invariant across the two pathways.

B.3.2 Existing-market storage proxy (terminal capacity)

Drewry reports that around 198 terminals can handle ammonia as a cargo, with a combined storage capacity of 9.6 Mm³ [147]. This value is used here as a proxy for global port/terminal storage capacity.

The total volume, V_{2024} of 9.6 Mm³, is converted into mass-equivalent storage capacity using the density of liquid ammonia, ρ_L at its boiling point (-33°C and 1 atm), following Equation (23):

$$S_{2024} = V_{2024} \cdot \rho_L = 6.5\ Mt \quad (23)$$

where V_{2024} is in Mm³, ρ_L in t/m³ (equal to 0.68, see Section 1.1).

B.3.3 New-market storage benchmark (IRENA)

IRENA provides an infrastructure sizing point for new-uses only: approximately 735 storage tanks of 50 kt each are required to provide about one week of storage (production and demand side) for new markets in the 1.5°C scenario in 2050 [9]. This implies, according to Equation (24):

$$S_{new,2050}^{1.5} = 735 \cdot 0.05\ Mt = 36.8\ Mt \tag{24}$$

B.3.4 New-market seaborne benchmark (IRENA)

IRENA also provides a benchmark for the seaborne transport requirement of new markets in the 1.5°C scenario in 2050 (Equation (25)):

$$T_{sea,new,2050}^{1.5} = 300\ \frac{Mt}{y} \tag{25}$$

This benchmark refers to new-market seaborne throughput only and excludes legacy seaborne trade associated with existing markets [9].

B.3.5 Baseline demand for scaling (2024)

To scale existing-market infrastructure from today to 2030/2050, a baseline existing-demand is required. A global ammonia consumption value of 190 Mt/y in 2024 (see Section 1.3) is used as a baseline for existing-market demand (Equation (26)):

$$D_{exist,2024} = 190\ \frac{Mt}{y} \tag{26}$$

this value is used to compute scaling factors for legacy infrastructure.

B.4 Assumptions

The following assumptions are applied explicitly:

- Assumption 1 (Linear scaling with demand for existing markets): Storage and legacy logistics flow for existing markets scale proportionally with $D^{s}_{exist,t}$;
- Assumption 2 (Linear scaling of new-market infrastructure with new-market demand): Storage and seaborne transport requirements for new markets scale proportionally with $D^{s}_{new,t}$ according to IRENA benchmark points for the 1.5°C scenario in 2050;
- Assumption 3 (Constant seaborne share for new uses in 1.5°C scenario): The seaborne fraction of new uses is inferred from IRENA 2050 benchmarks and applied to 2030. This is used as an allocation rule to and is not intended as a forecast of short-term future trade;
- Assumption 4 (Stated Policies benchmarks are downscaled from 1.5°C scenario): 2050 new-market benchmarks for storage and seaborne transport are scaled by the ratio of new-market demand (SP versus 1.5) and then scaled to 2030 using the SP demand ratio 2030/2050;
- Assumption 5 (Terminal-linked pipeline scaling for new uses): New-use pipeline throughput is assumed proportional to new-use seaborne throughput through a baseline pipeline-to-seaborne ratio β, calibrated from 2024 proxy baselines $T_{pipe,2024}/T_{sea,2024}$. β is treated as a range derived from the uncertainty in the 2024 legacy seaborne baseline (15–20 Mt/y). Pipelines are therefore interpreted as inland connectors that can link ports and hinterland clusters;
- Assumption 6 (Explicit pipeline baseline): Existing pipeline baseline is approximated as the sum of representative large systems, namely US Midwest (1.5 Mt/y), Italy (0.3 Mt/y), Togliatti–Odessa (2.5 Mt/y), accounting for a total of 4.3 Mt/y [148], [149].

B.5 Calculation steps

B.5.1 Existing-market scaling factors

Scaling factors for existing markets relative to the 2024 baseline are computed according to Equation (27):

$$f^{s}_{exist,t} = \frac{D^{s}_{exist,t}}{D_{exist,2024}} \; [-] \tag{27}$$

where $f^{s}_{exist,t}$ is dimensionless and is applied consistently to existing-market baseline stocks (storage) and flows (seaborne and pipeline throughput proxies).

B.5.2 Storage requirements

Storage capacity is calculated as the sum of an existing-markets component and a new-markets component, according to Equation (28):

$$S^{s}_{t} = S^{s}_{exist,t} + S^{s}_{new,t} \; [Mt] \tag{28}$$

where the existing-markets storage component is computed following Equation (29):

$$S^{s}_{exist,t} = S_{2024} \cdot f^{s}_{exist,t} \; [Mt] \tag{29}$$

and new-markets storage component for 2030 (1.5°C scenario) uses the IRENA benchmark and scales linearly by new-uses demand according to Equation (30):

$$S^{1.5}_{new,2030} = S^{1.5}_{new,2050} \cdot \frac{D^{1.5}_{new,2030}}{D^{1.5}_{new,2050}} \; [Mt] \tag{30}$$

New-markets storage component (Stated Policies scenario), first downscale the 2050 benchmark using Equation (31), then downscale to 2030 following Equation (32):

$$S^{SP}_{new,2050} = S^{1.5}_{new,2050} \cdot \frac{D^{SP}_{new,2050}}{D^{1.5}_{new,2050}} \; [Mt] \tag{31}$$

$$S^{SP}_{new,2030} = S^{SP}_{new,2050} \cdot \frac{D^{SP}_{new,2030}}{D^{SP}_{new,2050}} \; [Mt] \tag{32}$$

B.5.3 Seaborne transport requirement

Seaborne transport is calculated as legacy seaborne trade (existing markets) plus new-market seaborne flows according to Equation (33):

$$T^{s}_{sea,t} = T^{s}_{sea,exist,t} + T^{s}_{sea,new,t} \left[\frac{Mt}{y}\right] \tag{33}$$

the legacy seaborne trade baseline range is taken from Drewry [147]. $T_{sea,exist,2024}$ is in the range 15-20 Mt/y and scaled with existing-market demand following Equation (34):

$$T^{s}_{sea,exist,t} = T_{sea,exist,2024} \cdot f^{s}_{exist,t} \left[\frac{Mt}{y}\right] \tag{34}$$

From new-market seaborne flows, in the 1.5°C scenario for 2050, is possible to compute a constant seaborne share applicable also for the Stated Policies scenario (Assumption 3), and then downscaling it to 2030 (Assumption 4), according to Equation (35) and (36), respectively:

$$\alpha^{1.5}_{sea,new,2050} = \frac{T^{1.5}_{sea,new,2050}}{D^{1.5}_{new,2050}} = \frac{300 \; Mt/y}{354 \; Mt/y} \; [-] \tag{35}$$

$$T^{1.5}_{sea,new,2030} = \alpha^{1.5}_{sea,new,2050} \cdot D^{1.5}_{new,2030} \left[\frac{Mt}{y}\right] \quad (36)$$

where the new-market seaborne flow (Stated Policies) is obtained by first downscaling the 2050 ship benchmark (Equation (37)), and then downscale to 2030 (Equation (38)):

$$T^{SP}_{sea,new,2050} = \alpha^{1.5}_{sea,new,2050} \cdot D^{SP}_{new,2050} \left[\frac{Mt}{y}\right] \quad (37)$$

$$T^{SP}_{sea,new,2030} = T^{SP}_{sea,new,2050} \cdot \frac{D^{SP}_{new,2030}}{D^{SP}_{new,2050}} \left[\frac{Mt}{y}\right] \quad (38)$$

B.5.4 Pipeline transport requirement

Pipeline transport is computed as the sum of a scaled existing-pipeline component and a new-use component following Equation (39):

$$T^{s}_{pipe,t} = T^{s}_{pipe,exist,t} + T^{s}_{pipe,new,t} \left[\frac{Mt}{y}\right] \quad (39)$$

with the existing pipeline component calculated according to Equation (40):

$$T^{s}_{pipe,exist,t} = T_{pipe,exist,2024} \cdot f^{s}_{exist,t} \left[\frac{Mt}{y}\right] \quad (40)$$

where $T_{pipe,exist,2024}$ = 4.3 Mt/y (Assumption 6).

For new-use component (seaborne-linked scaling), pipelines are treated as inland logistics infrastructure that often complements seaborne trade by connecting terminals to hinterland clusters. In absence of scenario-specific IRENA pipeline sizing benchmarks, the new-use pipeline requirement is approximated as a fixed fraction β of the new-use seaborne throughput using Equation (41), (42) and (43):

$$\beta_{low} = \frac{T_{pipe,exist,2024}}{T_{sea,exist,2024-high}} = \frac{T_{pipe,exist,2024}}{20\,\frac{Mt}{y}} = 0.21\,[-] \tag{41}$$

$$\beta_{high} = \frac{T_{pipe,exist,2024}}{T_{sea,exist,2024-low}} = \frac{T_{pipe,exist,2024}}{15\,\frac{Mt}{y}} = 0.29\,[-] \tag{42}$$

$$T^{s}_{pipe,new,t} \in \left[\beta_{low} \cdot T^{s}_{sea,new,t}\,, \beta_{high} \cdot T^{s}_{sea,new,t}\right] \left[\frac{Mt}{y}\right] \tag{43}$$

B.6 Limitations and interpretation

- Storage: terminal capacity is used as a proxy for storage serving existing markets; it may include some non-industrial port capacity but provides a consistent global order-of-magnitude baseline;
- Seaborne transport: the method combines IRENA new-market benchmark with scaled legacy trade; results remain a range due to baseline trade and 2030 power-demand uncertainty. $\alpha^{1.5}_{sea,new,2050}$ is an allocation rule (not a forecast);
- Pipeline: β is a global calibration based on baseline proxies; it captures the order-of-magnitude linkage between terminal throughput and inland backbone capacity but does not represent a detailed regional network model. The resulting pipeline requirement should be interpreted as indicative inland throughput associated with terminal-hinterland connectivity and inland distribution.

List of figures

List of tables

List of acronyms

Acronym	Full-name
AC	Alternating Current
AEA	Ammonia Energy Association
AEGL	Acute Exposure Guideline Levels
AGR	Acid Gas Removal
APS	Announced Pledges Scenario
ASME	American Society of Mechanical Engineers
ASU	Air Separation Unit
ATR	Autothermal Reforming
BLS	Bureau of Labor Statistics
BoP	Balance of Plant
BPVC	Boiler and Pressure Vessels Code
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEF	Connecting Europe Facility
CFR	Cost and Freight
CLAS	Chemical Looping Ammonia Synthesis
CLMC	Chemical Looping Methane Cracking
CLP	Classification, Labelling and Packaging
CPI	Consumer Price Index
CPI-U	Consumer Price Index-Urban
DBD	Dielectric Barrier Discharge
DOT	Department Of Transportation
ENRR	Electochemical Nitrogen Reduction Reaction
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
EPC	Engineering Procurement and Construction
EPMA	Environmental Protection and Management Act

Acronym	Full-name
ERS	Emergency Release System
ESD	Emergency Shutdown
EU	European Union
FEED	Front-End Engineering Design
FID	Final Investment Decision
FOB	Free on Board
GHG	Greenhouse-gas
HER	Hydrogen Evolution Reaction
HICP	Harmonised Index of Consumer Price
HNS	Hazardous and Noxious Substances
HPGSA	High Pressure Gas Safety Act
HPGSCA	High Pressure Gas Safety Control Act
HS	Hazardous Substances
HTE	High-Temperature Electrolysis
IEA	International Energy Agency
IED	Industrial Emissions Directive
IGC	International Gas Carriers
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
ISPT	Institute for Sustainable Process Technology
JSA	Joint Study Agreement
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LGC	Large Gas Carrier
LPG	Liquefied Petroleum Gas
LTE	Low-Temperature Electrolysis
MGC	Medium Gas Carrier
MHI	Major Hazard Installations
NEA	National Environmental Agency
NZE	Net-Zero Emission Scenario
ONS	Office of National Statistics

Acronym	Full-name
OPRC	Protocol on Preparedness, Response and Co-operation to Pollution Incidents
OSHA	Occupational Safety and Health Administration
PEC	Photo-Electrochemical
PED	Pressure Equipment Directive
POX	Partial Oxidation
PPE	Personal Protective Equipment
Pre-FEED	Pre-Front-End Engineering Design
PSA	Pressure Swing Adsorption
RF	Radio Frequency
RTC	Rail Tank Car
SCC	Stress Corrosion Cracking
SDS	Sustainable Development Scenario
SEC	Security and Exchange Commission
SGC	Small Gas Carrier
SGS	Sour Gas Shift
SMR	Steam Methane Reforming
STEPS	Stated Policies Scenario
TRL	Technology Readiness Level
USA	United States of America
UV	Ultraviolet
VLGC	Very Large Gas Carrier
WGS	Water Gas Shift
WSH	Workplace Safety and Health

List of symbols

Symbol	Definition	Units
$\dot{Q}_{th}$	Thermal Power	MW
$\dot{W}_{el}$	Electrical power	MW
Q_{NH_3}	Annual Ammonia Production	t/y
$\dot{m}$	Mass Flowrate	kg/s
ΔH_f^0	Standard Entalphy of Formation	kJ/kmol
AF	Actualisation Factor	-
CAPEX	Total Capital Expenditure	€
CF	Currency conversion Factor	-
CRF	Capital Recovery Factor	y^{-1}
CS_{el}	Cost Share of electricity on LCOA	-
CS_i	Cost Share of fuel/feedstock on LCOA	-
CT	Carbon Tax	€/t_{CO2}
DSEC	Direct Specific Energy Consumption	MWh/t_{NH3}
IRR	Internal Rate of Return	-
LCOA	Levelised Cost Of Ammonia	€/t_{NH3}
LHV	Lower Heating Value	MJ/kg
NPV	Net Present Value	€
OPEX	Annual Operating Expenditure (fixed & variable)	€/y
PBT	Pay-Back Time	y
P_{el}	Price of electricity	€/MWh
P_i	Price of fuel/feedstock	€/GJ
P_{ng}	Natural gas price	€/GJ
Rev_i	Streams of revenues	€/t_{NH3}
s	Share of electricity production	-
S	Storage capacity	Mt
SE	Specific Emissions	t_{CO2}/t_{NH3}
SPEC	Specific Primary Energy Consumption	MWh/t_{NH3}

Symbol	Definition	Units
SRs	Scaling Ratios	-
T_{pipe}	Pipeline throughput	Mt/y
T_{sea}	Seaborne throughput	Mt/y
η	Efficiency	-

List of suffixes

Suffix	Definition
%	Percentage variation
0	Standard conditions
aux	Auxiliaries
ch	Chemical
el	Electrical
f	Formation
g	Gas-phase
s	Scenario
t	Timeline
T&S,CO_2	Transport and permanent storage of CO_2
tot	Total