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SUMMARY

This document provides the evidence and recommendations that shape the Green Ammonia methodology, ensuring its rules are transparent and grounded in the latest real-world data.

The analysis first shows that truly green ammonia is currently very rare and expensive, making up less than 1% of the global market and costing two to six times more than conventional ammonia. This confirms that green ammonia projects are not yet business-as-usual and need the financial support from carbon credits to be viable.

The report also explains why "blue" ammonia, which is made from fossil fuels with carbon capture, is not included in the methodology. A detailed assessment found that this technology carries a high risk of locking the world into using fossil fuel infrastructure for decades, which works against long-term climate goals.

To ensure emission reductions are measured fairly, the document sets a clear starting point (a "baseline") based on the performance of the most efficient conventional plants operating today. For example, it sets benchmarks of around 1.8 tonnes of CO_2 per tonne of ammonia for natural gas plants and 3.8 for coal plants. To drive continuous improvement, it also introduces a "downward adjustment factor"—a rule that makes the reduction targets stricter over time, in line with each country's national climate pledges.

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SECTION 1

Green vs. Conventional Ammonia production: Market Analysis

1| INTRODUCTION

Ammonia (NH_3) is one of the world's most produced bulk chemicals, primarily serving as the foundation for nitrogen-based fertilizers essential for global food security. It also finds applications in producing plastics, explosives, synthetic fibers, and refrigerants.[1] However, the dominant method of production carries a significant environmental footprint, prompting the development of alternative, low-carbon pathways. Understanding the distinction between conventional and green ammonia production is crucial for assessing the industry's transition towards sustainability.

1.1 | Conventional (Grey) Ammonia Production

The vast majority of ammonia produced today falls under the category of "grey" ammonia, signifying its reliance on fossil fuels and associated carbon dioxide (CO_2) emissions.[2] The most prevalent production method globally (over 70%) is Steam Methane Reforming (SMR), which primarily uses natural gas (methane(CH_4)) as both a feedstock and energy source.[3] Coal gasification is another significant route, particularly dominant in China.

The SMR process involves several key steps. First, methane reacts with steam at high temperatures and pressures over a catalyst to produce hydrogen (H_2) and carbon monoxide (CO) (reforming). Air is introduced to provide the necessary nitrogen (N_2) for ammonia synthesis and to generate heat through combustion.[4] Subsequently, the carbon monoxide reacts with steam in the water-gas shift reaction to produce more Hydrogen (H_2) and Carbon dioxide (CO_2). The CO_2 is then removed, typically through absorption processes. Finally, the purified hydrogen and nitrogen mixture is fed into the Haber-Bosch synthesis loop, where it reacts under high pressure (150–300 Bar) and temperature (400–500°C) over an iron-based catalyst to form Ammonia ($N_2 + 3H_2 \rightleftharpoons 2NH_3$).[5]

[1] Green ammonia - Iberdrola, accessed April 10, 2025

[2] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed April 10, 2025

[3] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed April 10, 2025

[4] The Future of Ammonia is Green, accessed April 10, 2025

[5] Green Ammonia - Fertilizer Industrial Services, accessed April 10, 2025

This conventional pathway is highly energy-intensive, consuming approximately 1.8-2% of global final energy annually.[6] More critically, it generates substantial greenhouse gas emissions. The SMR process itself releases significant amounts of CO_2, both from the chemical reactions and the combustion of fossil fuels for process heat. On average, producing one tonne of grey ammonia emits approximately 1.8 to 2.5 tonnes of CO_2. [7] Collectively, the ammonia industry is responsible for about 1.3-1.8% of global energy-related CO_2 emissions.[8]

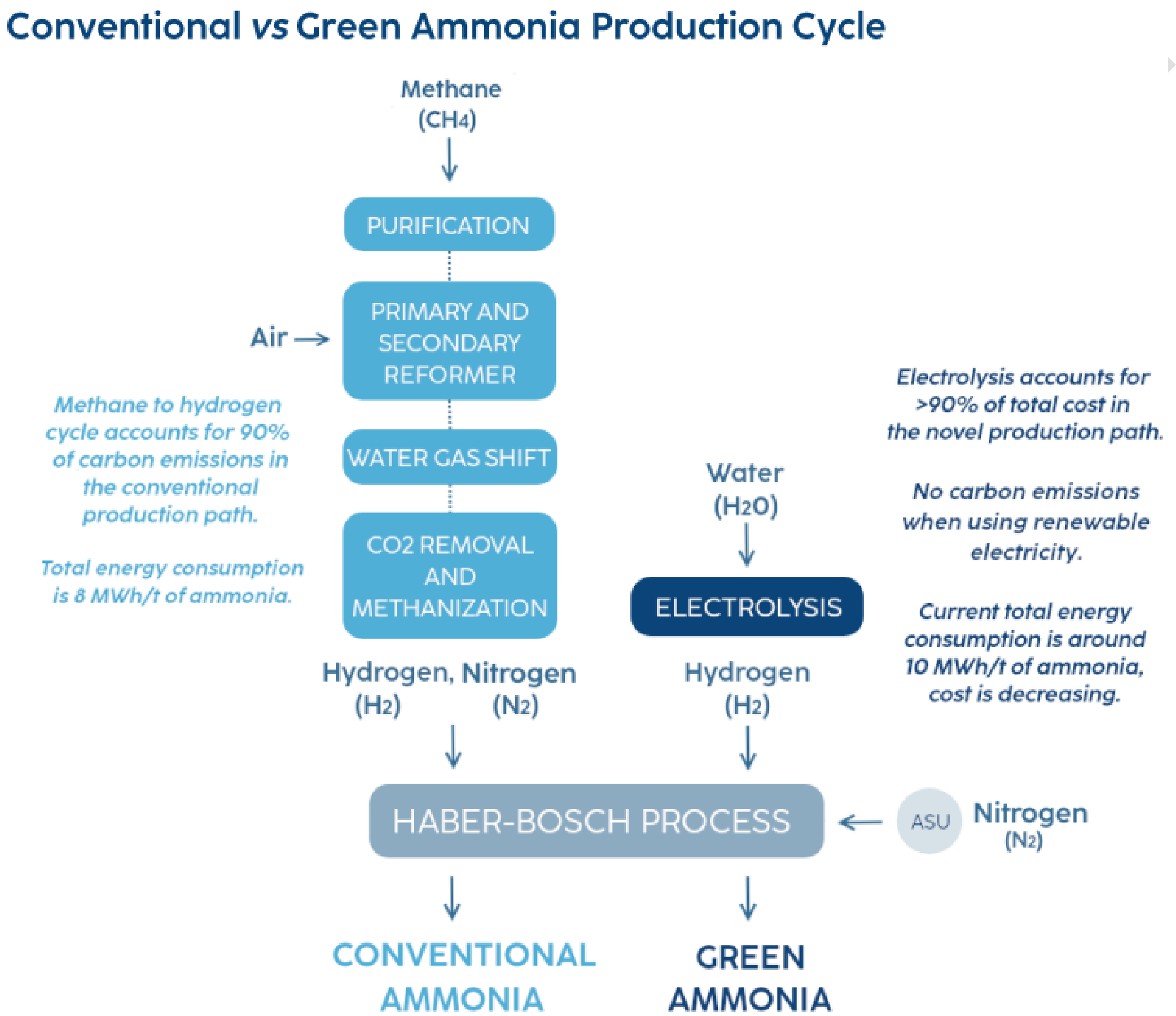

Figure 1 The production cycles of conventional ammonia and green ammonia (9)

Both SMR and the Haber-Bosch synthesis are technologically mature processes, optimized over decades.[10] This maturity, combined with the economies of scale

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[6] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed April 10, 2025

[7] Green ammonia - Iberdrola, accessed April 10, 2025

[8] Green Ammonia - Fertilizer Industrial Services, accessed April 10, 2025

[9] The Future of Ammonia is Green, accessed April 10, 2025

[10] What is Green Ammonia? How Is It Produced? - Blackridge Research & Consulting, accessed April 10, 2025

achieved in large, established plants, results in relatively low production costs, particularly in regions with access to inexpensive natural gas. However, this established nature presents a significant barrier to newer technologies. The existing infrastructure represents massive sunk capital investments with long operational lifetimes, often 20-50 years or more.[11] Displacing this incumbent requires low-carbon alternatives to overcome not only technological hurdles but also deeply entrenched economic factors and the inertia associated with these mature, large-scale assets.

1.2 | Green Ammonia Production

Green Ammonia is chemically identical to its conventional counterpart (NH_3) but is distinguished by its production process, which utilizes renewable energy sources and results in virtually zero direct CO_2 emissions. The defining feature of green ammonia production is the generation of "Green Hydrogen" through water electrolysis.

In this process, water (H_2O) is split into hydrogen (H_2) and oxygen (O_2) using electricity in an electrolyser. For the resulting hydrogen (and subsequently the ammonia) to be classified as "green," the electricity powering the electrolyser must come from renewable sources such as solar, wind, geothermal, or hydropower. Various electrolyser technologies exist, including Alkaline Water Electrolysis (AWE), Polymer Electrolyte Membrane (PEM) electrolysis, and Solid Oxide Electrolysis (SOE), each with different characteristics regarding maturity, cost, efficiency, and operational flexibility.[12]

Once green hydrogen is produced, it is combined with nitrogen. The nitrogen is typically obtained by separating it from the air using an Air Separation Unit (ASU), a process which also needs to be powered by renewable energy to maintain the "green" credentials of the final product. This green hydrogen and nitrogen mixture is then fed into the Haber-Bosch synthesis loop, the same core chemical process used in conventional ammonia production, to synthesize NH_3.

The production of green hydrogen via electrolysis is the critical differentiating step and accounts for the overwhelming majority (over 90%) of the total energy consumption in the green ammonia process.[13] This fundamentally alters the input requirements compared to grey ammonia. Instead of relying on fossil fuels as both feedstock and energy source, green ammonia production primarily depends on renewable electricity and water.[4] Consequently, the cost, scalability, and environmental profile of green ammonia are directly tied to the availability, cost, and carbon intensity of renewable electricity, as well as advancements in electrolyzer technology efficiency and cost reduction. [14] This linkage represents both the core challenge (high current costs, reliance on variable energy sources) and the core opportunity (potential for cost

[11] IEA's Ammonia Technology Roadmap IFA Summary for Policymakers - International Fertilizer Association, accessed April 10, 2025

[12] Comparison of Process Options for Sustainable Ammonia Production - Bryan Research & Engineering, LLC, accessed April 10, 2025

[13] The Future of Ammonia is Green, accessed April 10, 2025

[14] Green Ammonia - Fertilizer Industrial Services, accessed April 10, 2025

reduction aligned with falling renewable prices, decoupling from fossil fuel volatility) for green ammonia.

1.3 | Other Low-Carbon Pathways

Besides Grey and Green Ammonia, "Blue Ammonia" represents another significant pathway aimed at reducing the carbon footprint of ammonia production. [15] Blue ammonia production starts with the conventional SMR process using natural gas to produce hydrogen. However, it incorporates Carbon Capture, Utilization, and Storage (CCUS) technology to capture the CO_2 generated during the process, preventing most of it (typically over 90%) from being released into the atmosphere. The captured CO_2 is then typically transported and stored permanently underground in geological formations or potentially utilized in other industrial processes.
Blue ammonia is often viewed as a transitional or bridging technology. It allows leveraging existing SMR plant infrastructure and the mature Haber-Bosch process, potentially enabling faster deployment and larger scale-up compared to building entirely new greenfield green ammonia facilities.[16] While it significantly reduces emissions compared to grey ammonia, it still relies on fossil fuel feedstocks and the associated upstream emissions (e.g., methane leakage during natural gas extraction and transport). Economic analyses suggest that blue ammonia may be less expensive than green ammonia in the near term, particularly in regions with established natural gas infrastructure and suitable geology for CO_2 storage, and especially when supported by policy incentives like tax credits.[17] This potential cost advantage and ability to retrofit existing assets make blue ammonia both a competitor to green ammonia and a potentially significant contributor to decarbonizing the ammonia sector during the transition period. Investment decisions in the coming years may favor blue ammonia in certain contexts, potentially influencing the pace and specific pathway of the broader shift towards low-emission ammonia production.

2| GLOBAL AMMONIA PRODUCTION LANDSCAPE

The global ammonia market is vast and well-established, but currently overwhelmingly dominated by conventional production methods. Green ammonia is only beginning to emerge at a commercial scale.

2.1 | Conventional Ammonia Market: Global Capacity, Key Regions, and Producers

The global production capacity for conventional (primarily grey) ammonia is substantial. Estimates vary slightly depending on the source and year, but generally place current nameplate capacity in the range of 180 to 190 million tonnes per annum

[15] Green Ammonia - Fertilizer Industrial Services, accessed April 10, 2025

[16] Emerging role of blue and green ammonia in decarbonisation | Wood, accessed April 10, 2025

[17] Ammonia industry net-zero tracker - www3 .weforum .org /docs /WE, accessed April 10, 2025

(Mtpa).[18] The International Fertilizer Association (IFA) projected capacity would reach 207 Mtpa by 2028.[19] Actual global production is typically lower than nameplate capacity due to operational factors; the U.S. Geological Survey (USGS) estimated world production at approximately 150 Mtpa for 2023 and 2024.[20] A reasonable estimate for current global capacity is around 185-190 Mtpa, supporting actual production levels near 150 Mtpa. This production occurs across a large number of facilities, estimated at around 490 to 550 plants worldwide.[21]
Production is geographically concentrated, largely dictated by the availability of low-cost fossil fuel feedstocks (natural gas and coal) and proximity to major agricultural or industrial demand centers.[22] Key producing countries and their estimated share of global production/capacity include:

a. **China:** The world's largest producer, accounting for roughly 15-30% of the global total, heavily reliant on coal gasification.

b. **USA:** A major producer (around 9-10%), primarily using natural gas feedstock, with significant capacity concentrated in states like Louisiana, Oklahoma, and Texas near gas reserves.

c. **India:** Another major producer and consumer (around 8-10%), largely using natural gas.

d. **Russia:** A significant producer (around 10%) and major exporter, leveraging abundant natural gas.

e. **European Union (EU):** Collectively accounts for about 8%, mainly using natural gas, though production has faced curtailments due to high gas prices.[23]

f. **Middle East:** Countries like Qatar, Saudi Arabia, and Iran are significant producers due to vast natural gas resources. [24]

g. **Other notable producers:** Indonesia, Trinidad and Tobago (a major exporter), Canada, Egypt, Pakistan, Netherlands. [25]

This geographical concentration, tied to fossil fuel availability, underpins significant global trade flows and geopolitical factors. Russia, Trinidad and Tobago, and the

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[18] Green ammonia - Iberdrola, accessed April 10, 2025

[19] Global Fertilizer Market 2024 - Atlantic Project Cargo, accessed April 10, 2025

[20] NITROGEN (FIXED)—AMMONIA - USGS.gov, accessed April 10, 2025

[21] Major Ammonia Producing Companies and Their Capacities - Iamm.green, accessed April 10, 2025

[22] Ammonia Market Size, Growth & Trends Report by 2033 - Straits Research, accessed April 10, 2025

[23] Locating decentralised green ammonia production facilities, Clim-eat.org, accessed April 10, 2025,

[24] Major Ammonia Producing Companies and Their Capacities - Iamm.green, accessed April 10, 2025

[25] Major Ammonia Producing Companies and Their Capacities - Iamm.green, accessed April 10, 2025

Middle East are dominant exporters, while the EU, India, and the USA are major importers.

Table 1: Estimated Top Conventional Ammonia Producing Countries (Annual Production/Capacity)

Country	Estimated Annual Production/Capacity (Mtpa)	Primary Feedstock	Key Companies (Examples)
China	43 - 47	Coal, Natural Gas	Sinopec, CNPC
USA	14 - 15	Natural Gas	CF Industries, Nutrien, Koch
India	14 - 15	Natural Gas	IFFCO, GSFC, Chambal Fertilisers
Russia	~14	Natural Gas	EuroChem, PhosAgro, Togliattiazot
Indonesia	~6	Natural Gas	Pupuk Indonesia
Saudi Arabia	~5.4	Natural Gas	SABIC, Ma'aden
Egypt	4 - 5	Natural Gas	Fertiglobe (OCI/ADNOC), MOPCO
Canada	~3.6	Natural Gas	Nutrien, CF Industries
Trinidad & Tobago	~3.2-3.7	Natural Gas	Nutrien, Proman
Qatar	~3.1-3.8	Natural Gas	Qatar Fertiliser Company (QAFCO)

Note: Figures are estimates based on recent data and may represent either production or capacity. Company examples are illustrative.

2.2 | Commercial Green Ammonia Operations: Current Status

In sharp contrast to the established conventional market, commercial green ammonia production is still in its infancy. Global operational capacity derived purely from renewable electrolysis remains extremely limited. Estimates placed capacity at a mere 0.02 Mtpa (20 ktpa) in 2022.[26] By late 2023, this was projected to rise to around 185 ktpa, though this likely included various low-carbon definitions.[27] A more recent assessment by the Ammonia Energy Association (AEA) in August 2024 identified approximately 67.6 ktpa (0.068 Mtpa) of operational capacity specifically from low-emission plants utilizing water electrolysis.[28]

These operational facilities are typically small-scale, often serving as pilot or demonstration projects, or representing initial decarbonization steps at existing ammonia production sites. Key examples[29] of operational or recently commissioned commercial-scale green ammonia facilities (primarily electrolysis-based) include:

a. **Industrias Cachimayo (Cusco, Peru):** An older facility using hydropower, operational since 1965. While its specific current capacity isn't detailed, it's one of the last remaining "classical" electrolysis-based plants and now runs on 100% renewable energy.

[26] Locating decentralised green ammonia production facilities, Clim-eat.org, accessed April 10, 2025,

[27] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[28] Ammoniaenergy.org, accessed April 10, 2025,

[29] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

b. **Puertollano (Spain):** Operated by Iberdrola and Fertiberia, this plant uses a 20 MW PEM electrolyzer powered by solar PV and battery storage to produce green hydrogen, feeding Fertiberia's adjacent conventional ammonia plant. It has a capacity of approximately 17,000 tonnes NH_3 per year (17 ktpa) and became operational in 2022.

c. **Porsgrunn (Norway):** Yara installed a 24 MW PEM electrolyzer system powered by Norway's hydro-rich grid to partially decarbonize its existing large ammonia plant. It produces approximately 20,500 to 25,000 tonnes NH_3 per year (20.5-25 ktpa) and started operations in 2023/2024.

d. **Donaldsonville (Louisiana, USA):** CF Industries commissioned a 20 MW alkaline electrolyzer system, connected to the grid with a renewable power purchase agreement (PPA), to supply green hydrogen to its massive ammonia complex. It produces approximately 20,000 tonnes NH_3 per year (20 ktpa) and became operational in 2023/2024.

e. **Bikaner (Rajasthan, India):** ACME Group operates a pilot plant powered by solar PV, using a 4 MW alkaline electrolyzer system, producing around 1,500 tonnes NH_3 per year (1.5 ktpa). It commenced operations in November 2021 and serves as a proof-of-concept.

f. **China (Unspecified):** An AEA report notes a flexible green ammonia plant using water electrolysis powered by renewables became operational in China in 2024, with a capacity of 20,000 tonnes NH_3 per year (20 ktpa).[30]

g. **USA & Canada (Unspecified Small-Scale):** The same AEA report identifies two additional small-scale plants becoming operational in 2024: one in the US (7 ktpa) and one in Canada (0.1 ktpa), both using water electrolysis.

Other smaller pilot or demonstration projects have also been reported in locations like Taranaki (New Zealand), Duqm (Oman), Port Lincoln (Australia), Western Jutland (Denmark), Ogata Village and Koriyama (Japan), Morris (Minnesota, USA), and Harwell (UK), often with capacities well below 1 ktpa (e.g., Harwell reported 30 kg/day).[31]

The current landscape clearly shows that operational green ammonia capacity is fragmented and primarily consists of these early-stage projects. Many involve adding electrolyser to supply a fraction of the hydrogen needed at existing large conventional plants, allowing companies to gain operational experience and test the integration of electrolysis with ammonia synthesis. This pattern signifies an industry in the initial phases of commercialization, focused on technology demonstration and de-risking rather than achieving significant market volume.

[30] Ammoniaenergy.org, accessed April 10, 2025,

[31] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

Table 2: Selected Operational Commercial-Scale Green Ammonia Plants (Electrolysis-Based, as of late 2024)

Location (Country, Site)	Operator(s)	Capacity (ktpa NH_3)	Electrolyzer Type/Size (MW)	Energy Source	Status/Start Year
Porsgrunn, Norway	Yara International	20.5 - 25	PEM / 24 MW	Hydro / Grid	Operational 2024
Donaldsonville, LA, USA	CF Industries	~20	Alkaline / 20 MW	Grid / PPA	Operational 2024
China (Unspecified)	Unspecified	~20	Alkaline / Size N/A	Renewables	Operational 2024
Puertollano, Spain	Iberdrola / Fertiberia	~17	PEM / 20 MW	Solar / Battery	Operational 2022
USA (Unspecified)	Unspecified	~7	Alkaline / Size N/A	Water Electrolysis	Operational 2024
Bikaner, India	ACME Group (Pilot)	~1.5	Alkaline / 4 MW	Solar	Operational 2021
Canada (Unspecified)	Unspecified	~0.1	Alkaline / Size N/A	Water Electrolysis	Operational 2024

Note: Based on available data. Capacities and start years are approximate. Focuses on plants >0.1 ktpa with confirmed operational status post-2020.

3| CURRENT PENETRATION RATE OF COMMERCIAL GREEN AMMONIA

3.1 | Calculation and Analysis of Green Ammonia's Market Share

To determine the current market penetration of commercial green ammonia, its operational capacity must be compared against the total global ammonia production capacity (conventional plus green).

Based on the latest available data, the total operational capacity of commercial-scale green ammonia plants using renewable electrolysis is approximately 67.6 ktpa, which equates to about 0.068 Mtpa.[32] The total global ammonia capacity is estimated to be in the range of 185-190 Mtpa. Adding the nascent green capacity does not significantly alter this total.

Using a mid-range total global capacity estimate of approximately 188 Mtpa, the penetration rate can be calculated as:

Penetration Rate = (Total Green Ammonia Capacity / Total Global Ammonia Capacity) * 100%

Penetration Rate = (0.068 Mtpa / 188 Mtpa) * 100%

Penetration Rate ≈ 0.036%

This calculation starkly illustrates that the current penetration rate of commercial green ammonia is extremely low, representing significantly less than one-tenth of one percent (0.1%) of the global ammonia market by capacity.

The implications of this minuscule market share are clear: green ammonia is currently a niche product with a negligible impact on overall ammonia supply volumes.[33] Its present role is largely confined to supplying pilot projects, facilitating initial

[32] Ammoniaenergy.org, accessed April 10, 2025,

[33] Green Ammonia vs. Regular Ammonia Production, accessed April 10, 2025,

decarbonization efforts at existing facilities by displacing small amounts of grey hydrogen, or meeting early demand from customers seeking certified green products, potentially at a premium price.

4| GEOGRAPHICAL DISTRIBUTION ANALYSIS

The geographical footprints of conventional and green ammonia production differ significantly, reflecting their distinct primary drivers: fossil fuel availability versus renewable energy potential.

4.1 | Conventional Ammonia Production Hubs

As discussed above, the conventional ammonia production is heavily concentrated in specific regions around the globe. China, the USA, India, Russia, the European Union, the Middle East (particularly Qatar, Saudi Arabia, Iran), and Trinidad and Tobago stand out as major production centers.[34]

The primary determinant for this geographical distribution has historically been access to abundant and low-cost fossil fuel feedstocks – predominantly natural gas, but also coal, especially in China.[35] Proximity to large agricultural markets, such as the US Midwest corn belt or the intensive farming regions of India and China, also plays a role, although the existence of significant global ammonia trade and established transport infrastructure (including pipelines in the US and Europe[36]) allows production hubs to serve distant markets.

This geography is largely path-dependent, reflecting decades of investment locked into locations optimized for fossil fuel access. The high capital cost and long lifespan of conventional ammonia plants create significant geographical inertia. Feedstock price volatility directly impacts regional competitiveness, as seen with production curtailments in Europe due to high natural gas prices.[37] This established map dictates global trade flows and intrinsically links the ammonia and fertilizer markets to fossil fuel geopolitics and price fluctuations.

4.2 | Emerging Green Ammonia Locations

The nascent geography of green ammonia production presents a contrasting picture, driven primarily by the availability of high-quality renewable energy resources rather than fossil fuels. The limited number of currently *operational* commercial or pilot-scale green ammonia plants are scattered across various locations, including Peru, Spain, Norway, the USA (Louisiana), India, China, Canada, and potentially others like New

[34] Ammonia Market Size, Growth & Trends Report by 2033 - Straits Research, accessed April 10, 2025

[35] Ammonia Market Size, Growth & Trends Report by 2033 - Straits Research, accessed April 10, 2025

[36] Developing a Green Ammonia Project - EPCM Holdings, accessed April 10, 2025

[37] Major Ammonia Producing Companies and Their Capacities - Iamm.green, accessed April 10, 2025

Zealand, Oman, Australia, Denmark, Japan, and the UK, reflecting early adoption and testing in diverse settings. [38]
However, the map of *announced and pipeline* projects reveals emerging hotspots for future large-scale green ammonia development. These locations are characterized by exceptional solar irradiation, strong and consistent wind resources, or significant hydropower potential. Key regions attracting major project announcements[39],[40] include:

a. **Australia:** Particularly Western Australia (Pilbara, Murchison regions) and South Australia, leveraging vast solar and wind potential for export-oriented projects.

b. **Middle East & North Africa (MENA):** Saudi Arabia (NEOM project), Oman (Duqm, Salalah regions), the UAE, and Egypt are planning GW-scale projects, capitalizing on excellent solar resources and strategic locations for export.

c. **North America:** The US Gulf Coast (leveraging existing infrastructure and potential offshore wind/solar) and Texas (solar/wind) are key areas, alongside projects in Canada.

d. **Latin America:** Chile (Atacama Desert solar) and Brazil (wind/hydro/solar potential) are prominent locations for planned export projects.

e. **Europe:** Spain (solar), Norway (hydro), and potentially locations with strong offshore wind resources (e.g., Netherlands, Germany, UK) are active, though often focused on decarbonizing existing industry or regional use.

f. **Other areas:** Morocco and India are also pursuing significant green ammonia projects, often linked to domestic fertilizer needs or export ambitions.

Beyond renewable energy availability, factors like access to sufficient water for electrolysis[41], availability of land, stable regulatory frameworks, and proximity to ports or infrastructure suitable for export are crucial for these large-scale developments.[42] The strong focus on export markets in many announced mega-projects suggests a potential future where green ammonia becomes a globally traded energy commodity, produced in resource-rich locations and shipped to demand centers.

4.3 | Comparative Geographical Footprint

Comparing the two footprints reveals a potential major shift in the global ammonia landscape. Conventional production is tied to the geography of fossil fuels. Green

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[38] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[39] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[40] Green Ammonia Market Size, Share | Growth Report [2024-2032], accessed April 10, 2025

[41] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[42] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

ammonia production is being driven by the geography of renewables. While some overlaps exist (e.g., the US Gulf Coast possesses both natural gas resources and growing renewable potential, potentially supporting both blue and green ammonia), significant divergences are emerging. Regions like Australia and Chile, not major conventional ammonia players, could become green ammonia powerhouses.
This shift could fundamentally alter global energy and chemical trade dynamics. Countries rich in renewable resources could become major energy exporters via green ammonia, potentially enhancing energy security for importing nations currently reliant on fossil fuels. However, realizing this potential requires massive investment in new production facilities and associated infrastructure, including renewable generation, transmission, electrolysers, ASUs, ammonia synthesis loops, storage tanks, dedicated port facilities, and potentially a fleet of specialized ammonia carriers.
Furthermore, green ammonia offers a potential for geographical diversification through decentralization. Unlike the large, centralized SMR plants dictated by economies of scale, green ammonia production, particularly the electrolysis front-end, can be modular. This opens the possibility for smaller-scale, distributed green ammonia (DGA) production facilities located closer to end-users, such as agricultural cooperatives or industrial sites.[43] Such systems could reduce transportation costs and associated emissions, improve supply reliability, offer more stable pricing decoupled from global commodity markets, and enhance access for remote communities. This contrasts sharply with the highly centralized nature of conventional ammonia production.[44] Therefore, the future geographical footprint of ammonia may be characterized by a dual structure: large-scale, export-oriented hubs in optimal renewable locations, complemented by smaller, distributed production serving local or regional needs. However, efficiently scaling down the Haber-Bosch process or developing alternative, small-scale synthesis technologies remains a challenge for the DGA model.[45]

5| COMPARATIVE ANALYSIS: GREEN VS. CONVENTIONAL AMMONIA PLANTS

Significant differences exist between conventional (grey) and green ammonia production facilities in terms of their typical scale, technological maturity, and operational characteristics.

5.1 | Production Scale and Capacity Differences

A defining characteristic of the conventional ammonia industry is its operation at very large scales, driven by the pursuit of economies of scale, particularly in the SMR or Autothermal Reforming (ATR) hydrogen production units and the Haber-Bosch

43 Green Ammonia vs. Regular Ammonia Production, accessed April 10, 2025,

44 Seeding a New Pathway: The Opportunity for Distributed Green Ammonia - RMI, accessed April 10, 2025

45 Green Ammonia – An Alternative Fuel - FutureBridge, accessed April 10, 2025

synthesis loop.[46] A typical modern, world-scale conventional ammonia plant based on natural gas has a single-train production capacity ranging from 2,000 to 3,300 tonnes per day (tpd), translating to approximately 0.7 to 1.2 Mtpa.[47] The largest single-train plants currently operational can reach capacities of 3,760 tpd (about 1.3 Mtpa). [48] Some production sites host multiple trains, achieving total site capacities exceeding 4 Mtpa. Furthermore, newer designs incorporating ATR technology aim for even larger single-train capacities, potentially reaching 4,000-6,000 tpd (1.4-2.1 Mtpa), with some technology licensors offering designs up to 10,000 tpd (3.5 Mtpa).[49]

In stark contrast, currently operational green ammonia plants are significantly smaller. As detailed above, most are pilot or demonstration facilities with capacities typically below 30 ktpa (less than 100 tpd).[50] These plants are often an order of magnitude smaller than typical grey ammonia plants. This limited scale is primarily constrained by the capacity and cost of the electrolyzer units used for green hydrogen production.

However, the ambition for future green ammonia projects is rapidly scaling up to match and potentially exceed conventional plant sizes. Numerous announced projects are targeting capacities in the range of 1-3 Mtpa. Notable examples include the NEOM project in Saudi Arabia (targeting 1.2 Mtpa) and the Murchison project in Australia (targeting ~1.8-1.9 Mtpa).[51] Achieving such scales necessitates deploying electrolyzer capacity measured in gigawatts (GW) – for instance, the NEOM project plans for 2.2 GW of electrolysis powered by over 4 GW of renewables[52], and a hypothetical 10,000 tpd green ammonia plant could require 5.4–7.5 GW of electrolyzers.[53] This demonstrates that while current green ammonia operations are small, the industry is aiming for parity with conventional scale in its next generation of projects, recognizing that achieving cost-competitiveness likely requires leveraging economies of scale in both massive renewable energy deployment and large-scale electrolysis and ammonia synthesis.

5.2 | Technological Maturity and Process Variations

Conventional ammonia production relies on technologies that are highly mature and have been optimized over a century. Steam Methane Reforming and the Haber-Bosch process are well-understood, reliable technologies with established supply chains and

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[46] Production technology updates: from mega-scale to distributed ammonia, accessed April 10, 2025

[47] Innovation Outlook: Renewable Ammonia - IRENA, accessed April 10, 2025,

[48] Production technology updates: from mega-scale to distributed ammonia, accessed April 10, 2025

[49] Innovation Outlook: Renewable Ammonia - IRENA, accessed April 10, 2025,

[50] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[51] CIP Secures Funding for Murchison Green Hydrogen Project in Australia, accessed April 10, 2025

[52] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

operational expertise. The process involves multiple integrated steps: feedstock purification, reforming, water-gas shift conversion, CO_2 removal, methanation (to remove residual carbon oxides), compression, and finally, ammonia synthesis in the Haber-Bosch loop.

Green ammonia production leverages the mature Haber-Bosch synthesis backend but replaces the fossil-fuel-based hydrogen production front-end with water electrolysis powered by renewables. While Haber-Bosch itself is mature, its integration with large-scale, potentially variable hydrogen supply from electrolysis is a newer challenge. Electrolysis technologies (AWE, PEM, SOE) are themselves at varying stages of maturity. While AWE is more established, PEM offers potentially greater flexibility, and SOE promises higher efficiency but is less mature.[53] All are undergoing rapid development to improve efficiency, reduce costs, and scale up manufacturing capacity to meet the projected GW-level demand from large green ammonia projects. The green ammonia process flow is potentially simpler on paper (water splitting via electrolysis, nitrogen separation from air via ASU, ammonia synthesis), but the integration of these components, especially with variable power input, presents unique engineering challenges. Alternative pathways for green ammonia, such as direct electrochemical synthesis from nitrogen and water, biological synthesis using enzymes, or chemical looping processes, are at much lower technology readiness levels (TRL 1-4) and are not yet commercially viable for large-scale production.[54]

This difference in technological maturity creates a distinct risk-reward profile. Conventional ammonia benefits from proven reliability and predictable costs but faces increasing pressure due to its emissions. Green ammonia offers a zero-emission production pathway but relies on a rapidly evolving (electrolysis) front-end technology, introducing risks related to cost projections, scaling, long-term performance, and operational integration, alongside the opportunity for significant cost reductions through continued innovation.

5.3 | Operational Characteristics and Challenges (Energy, Emissions, Flexibility)

The operational characteristics of green and conventional ammonia plants differ significantly, primarily due to their different energy sources and process configurations.

a. **Energy Consumption:** Both processes are energy intensive. Conventional SMR-based production consumes significant amounts of natural gas, both as feedstock and fuel, with total energy consumption around 8 MWh per tonne of ammonia, contributing to the sector's ~1.8-2% share of global energy use.[55] Green ammonia production via electrolysis is also highly energy-intensive, but the input is primarily electricity. Estimates suggest an electricity requirement of

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[53] Comparison of Process Options for Sustainable Ammonia Production - Bryan Research & Engineering, LLC, accessed April 10, 2025

[54] Green Ammonia – An Alternative Fuel - FutureBridge, accessed April 10, 2025,

[55] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed April 10, 2025

approximately 9-10 MWh per tonne of ammonia, mostly for the electrolysis step.[56] The overall energy efficiency of power-to-ammonia can be relatively high (potentially >70% system efficiency cited for SOE-based routes) compared to biomass-to-ammonia or conventional methane-to-ammonia, but this depends heavily on electrolyzer efficiency.[57]

b. **Emissions:** Conventional production results in high CO_2 emissions, typically 1.8-2.5 tonnes CO_2 per tonne of ammonia produced.[58] Green ammonia production, using renewable electricity, has near-zero direct CO_2 emissions. However, it is important to note that if green ammonia is later used as a fuel (e.g., in ships or power plants), its combustion can produce nitrogen oxides (NO_x) and nitrous oxide (N_2O), which are potent air pollutants and greenhouse gases, respectively. Managing these downstream emissions is a critical challenge for ammonia's potential use as a clean fuel.[59]

c. **Feedstock:** Conventional plants rely on fossil fuels (natural gas, coal, oil). Green plants primarily require water (for electrolysis) and air (as the source of nitrogen). Access to sufficient freshwater resources can be a constraint for large-scale green ammonia production, potentially necessitating desalination (which adds energy cost) in arid regions.

d. **Operational Flexibility:** Conventional ammonia plants, particularly the Haber-Bosch synthesis loop, are designed for and operate most efficiently under stable, continuous (24/7) conditions.[60] They have limited flexibility to rapidly ramp production up or down. Green ammonia plants powered by intermittent renewable sources like solar and wind face the challenge of integrating a variable power supply with the steady-state requirements of the ammonia synthesis process. This necessitates strategies such as incorporating energy storage (e.g., batteries), hydrogen storage (to buffer the H_2 supply to the Haber-Bosch loop), oversizing renewable generation and electrolysis capacity, or developing more flexible ammonia synthesis processes. These solutions add complexity and cost to green ammonia production.

e. **Cost:** Currently, green ammonia production costs are significantly higher than conventional grey ammonia costs. Estimates suggest green ammonia can cost anywhere from 10% higher to more than double the cost of grey ammonia, or even six times higher depending on assumptions.[61] The primary drivers of green ammonia cost are the price of renewable electricity and the capital

[56] Green Ammonia vs. Regular Ammonia Production, accessed April 10, 2025

[57] Implications of the Inflation Reduction Act on Deployment of Low-Carbon Ammonia Technologies - mit ceepr, accessed April 10, 2025

[58] Green ammonia - Iberdrola, accessed April 10, 2025

[59] Ammonia: zero-carbon fertiliser, fuel and energy store - Royal Society, accessed April 10, 2025

[60] Green ammonia production: harnessing green hydrogen, accessed April 10, 2025

[61] IEA's Ammonia Technology Roadmap IFA Summary for Policymakers - International Fertilizer Association, accessed April 10, 2025,

expenditure (CAPEX) for electrolysers. Blue ammonia costs are generally considered to be intermediate between grey and green.[62] Green ammonia is projected to become cost-competitive with grey ammonia only under scenarios with very low renewable electricity prices (e.g., below $20/MWh) or significant carbon pricing applied to grey ammonia emissions (e.g., >$150/tonne CO_2).[63] Policy incentives, such as the production tax credits in the US Inflation Reduction Act (IRA), can substantially improve the economics of both blue and green ammonia, potentially making them competitive with or even cheaper than unabated grey ammonia.[64]

In essence, the transition from conventional to green ammonia involves trading dependence on fossil fuels and the associated CO_2 emissions for a reliance on vast amounts of clean electricity and the technical and economic challenges of managing potentially intermittent power sources and higher initial capital costs. The environmental benefits are clear at the production stage, but achieving cost parity and overcoming operational hurdles remain key objectives.

Table 3: Comparative Summary: Green vs. Conventional Ammonia Production Characteristics

Feature	Conventional (Grey) Ammonia	Green Ammonia
Primary Feedstock	Natural Gas, Coal, Oil	Water, Air (Nitrogen)
Primary Energy Source	Fossil Fuels (for heat & H_2 production)	Renewable Electricity (for electrolysis & process)
Key Technology (H2 Production)	Steam Methane Reforming (SMR), Autothermal Reforming (ATR), Coal Gasification	Water Electrolysis (AWE, PEM, SOE)
CO2 Emissions (Production)	High (1.8-2.5 tCO_2/tNH_3)	Near-Zero
Typical Plant Scale (Current)	Large (0.7-3.5 Mtpa)	Small (Pilot/Demo, <0.03 Mtpa)
Technological Maturity	Very High (SMR, Haber-Bosch)	Moderate/Developing (Electrolysis Integration)
Operational Flexibility	Low (prefers stable operation)	Challenged by intermittency, requires storage/flexibility solutions
Relative Cost (Current)	Lowest	Significantly Higher (2x - 6x grey)
Key Challenges	High CO_2 emissions, fossil fuel price volatility	High cost (electricity, CAPEX), managing intermittency, scaling electrolysis, securing offtake

[62] Ammonia industry net-zero tracker - www3 .weforum .org /docs /WE, accessed April 10, 2025

[63] Sustainability Assessment of Green Ammonia Production To Promote Industrial Decarbonization in Spain - PMC, accessed April 10, 2025

[64] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed April 10, 2025

6| NEAR-TERM GROWTH POTENTIAL AND FUTURE OUTLOOK

While current commercial green ammonia production is minimal, the future outlook is characterized by significant ambition, driven by global decarbonization efforts and emerging new markets for ammonia.

6.1 | Major Announced Green Ammonia Projects (Under Construction / Late-Stage)

A vast pipeline of low-emission ammonia projects (both green and blue) has been announced globally. The Ammonia Energy Association tracked a total announced capacity of 372.5 million tonnes per annum (Mtpa) across 428 projects as of August 2024.[65] However, it is crucial to recognize that the vast majority of these projects are still in the early stages of development (feasibility studies or conceptual design).[66] Only a small fraction have reached a Final Investment Decision (FID) or are currently under construction.

Focusing on larger projects (>500 ktpa capacity) that are considered 'Firm' (FID reached or under construction) or 'Mature' (demonstrating significant progress towards FID, such as securing key permits, offtake agreements, or EPC contracts) provides a more realistic view of near-term capacity additions. Based on AEA's classification system[67] and project announcements, key examples include:

a. **Firm / Under Construction:**
    i. **NEOM Green Hydrogen Project (Saudi Arabia):** A flagship green ammonia project targeting 1.2 Mtpa capacity using 2.2 GW of electrolysis powered by over 4 GW of dedicated wind and solar energy. FID was announced in May 2023 with a total investment of $8.4 billion. Construction is well underway (reportedly 60% complete as of December 2024) with commercial operations targeted for 2026. Air Products is the EPC contractor and has secured exclusive offtake for the entire ammonia output for 30 years.
    ii. **CF Industries / Mitsui / JERA Low-Emission Ammonia (Louisiana, USA):** A $4 billion project targeting 1.1 Mtpa of low-emission ammonia, likely blue ammonia using SMR with CCUS. FID was announced in April 2025.[68] This likely corresponds to the 'Beaumont Low-carbon fossil ammonia project' listed by AEA as 'Firm' with a 1.1 Mtpa capacity using gas reforming, expected online in 2025.

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[65] ammoniaenergy.org, accessed April 10, 2025

[66] Global Hydrogen Review 2024: FID doubles, low-emission ammonia takes center stage, accessed April 10, 2025

[67] ammoniaenergy.org, accessed April 10, 2025

[68] Ammonia Energy Association, accessed April 10, 2025

iii. **TA'ZIZ Blue Ammonia (Abu Dhabi, UAE):** A project targeting 1.1 Mtpa of blue ammonia using gas reforming with CCUS. It is reported as under construction with a target start date of 2027. [69]

b. **Mature / Developing (Approaching FID or Significant Progress):**

i. **ACME Green Ammonia Project (Duqm, Oman):** Being developed in phases. Phase 1 targets 0.1 Mtpa green ammonia using ~320 MW of electrolysis, powered by dedicated solar. FID for Phase 1 has been achieved, financing secured (partially via REC loan), long-lead items ordered, and construction activities have commenced, targeting commercial operation by Q1 2027. A binding offtake agreement for Phase 1 output is in place with Yara Clean Ammonia. Phase 2 aims to expand capacity significantly towards a total of 0.9-1.2 Mtpa.[70]

ii. **Murchison Green Hydrogen Project (Western Australia):** A large-scale green ammonia export project targeting ~1.8-1.9 Mtpa total capacity, powered by 6 GW of onshore wind and solar. Led by Copenhagen Infrastructure Partners (CIP). The project has received a conditional funding commitment of AUD 814 million under Australia's Hydrogen Headstart program for an initial phase of ~1.5 GW electrolyser capacity (~0.9 Mtpa ammonia). It is currently pre-FID, undergoing environmental assessments, with construction targeted to start in 2027 and first production around 2031.

iii. **Salala H_2 Project (Salalah, Oman):** A consortium including OQ, Marubeni, Dutco, and Samsung C&T plans to produce over 1 Mtpa of green ammonia, utilizing over 4 GW of renewable energy to power electrolyzers producing over 175 ktpa of green hydrogen. The project was awarded a land block by Hydrom in December 2023 and is currently pre-FID.[71]

iv. **Hyport Duqm Project (Oman):** A joint venture including OQ, DEME, and bp. Phase 1 aims for ~0.33 Mtpa green ammonia (from 60 ktpa H_2) using 500 MW of electrolysis powered by 1.4 GW of renewables. It is considered one of Oman's leading projects, potentially targeting FID in 2026-27.[47]

Many other large-scale projects exist in the pipeline across Spain, the US, Netherlands, Germany, Chile, Brazil, Egypt, India, and elsewhere, but remain further from FID. Accessing comprehensive, up-to-date project details often requires specialized databases like those maintained by the IEA or commercial intelligence providers.
A critical observation is the significant gap between the vast scale of announced projects and the limited number progressing through the crucial stages of securing

[69] Ammonia Energy Association, accessed April 10, 2025

[70] Oman Green Ammonia Project Showcase World Hydrogen MENA, accessed April 10, 2025

[71] Topic: Mega-project - Ammonia Energy Association, accessed April 10, 2025

financing (reaching FID) and commencing construction.[72] While multi-billion dollar investments like NEOM demonstrate that large-scale green ammonia projects are technically and financially feasible under the right conditions (including strong government backing and secured long-term offtake), converting the broader pipeline into reality faces major hurdles. Securing bankable, long-term offtake agreements at prices that cover the high production costs of early projects is repeatedly cited as a primary bottleneck for developers seeking project finance.[73] Cost inflation, supply chain constraints, and evolving policy landscapes add further complexity and uncertainty.[74] This suggests that while the ambition for green ammonia is high, realizing that ambition in the near term will be challenging.

Table 4: Major Announced Low-Emission Ammonia Projects (>500 ktpa, Selected Firm/Mature/Developing)

Project Name	Location (Country)	Operator(s) / Developers	Capacity (Mtpa NH3)	Technology (Green/Blue, Electrolyser GW if Green)	Status (as of early 2025)	Target Start Year	Notes
NEOM Green Hydrogen Project	Saudi Arabia	NGHC (ACWA Power, Air Products, NEOM)	1.2	Green / 2.2 GW Electrolysis	Under Construction	2026	$8.4bn FID May 2023, Air Products 30yr offtake
Beaumont Low-Carbon Ammonia (CF/Mitsui/JERA)	USA (Louisiana)	CF Industries, Mitsui & Co., JERA	1.1	Blue (Gas Reforming + CCS assumed)	FID Reached (Apr 2025)	2025	$4bn investment
TA'ZIZ Blue Ammonia	UAE (Abu Dhabi)	ADNOC, Fertiglobe, GS Energy, Mitsui	1.1	Blue (Gas Reforming + CCS)	Under Construction	2027	
ACME Green Ammonia Project (Total)	Oman (Duqm)	ACME Group, Scatec	0.9 - 1.2 (target)	Green / ~3.5 GW Electrolysis (target)	Phase 1 (0.1 Mtpa) FID/Construction	Q1 2027 (Phase 1)	Yara offtake for Phase 1
Murchison Green Hydrogen Project	Australia (WA)	Copenhagen Infrastructure Partners (CIP)	~1.8 - 1.9 (target)	Green / ~3 GW Electrolysis (target)	Pre-FID / Developing	~2031	Headstart funding awarded (conditional)
SalalaH$_2$ Project	Oman (Salalah)	OQ, Marubeni, Dutco, Samsung C&T	>1.0 (target)	Green / >4 GW Renewables (Electrolyser size N/A)	Pre-FID / Developing	N/A	Land awarded Dec 2023
Hyport Duqm Project (Phase 1)	Oman (Duqm)	OQ Alternative Energy, DEME Concessions, bp	0.33	Green / 0.5 GW Electrolysis	Pre-FID / Developing	~2026-27?	

Note: Based on available data. Status and timelines are subject to change. N/A = Not Available/Not Specified.

[72] Global Hydrogen Review 2024: FID doubles, low-emission ammonia takes center stage, accessed April 10, 2025

[73] Global Hydrogen Review 2024: FID doubles, low-emission ammonia takes center stage, accessed April 10, 2025

[74] Big ambitions but slow progress: global hydrogen market developments in Q4 2023, accessed April 10, 2025

6.2 | Projected Capacity Growth and Market Trends

Despite the challenges, projections indicate substantial growth in low-emission ammonia capacity over the coming decade. The AEA anticipates that by 2030, approximately 30.6 Mtpa of low-emission and transitional ammonia capacity could be operational, based on projects currently classified as Operational, Firm, or Mature.[75] This includes a significant contribution from both blue ammonia (gas reformation with CCS, projected at 14.0 Mtpa) and green ammonia (water electrolysis, projected at 10.5 Mtpa), along with existing transitional capacity (likely older plants or those with partial CCS/renewable integration, totaling 5.8 Mtpa).[76] Earlier estimates from 2022 suggested a planned capacity of 15 Mtpa by 2030.[77] Achieving the higher end of these projections is critical for aligning the sector with pathways compatible with the Paris Agreement goals or Net Zero by 2050 scenarios, which require rapid and deep emissions reductions.

One market research report projected the market size increasing from approximately USD 47 million in 2023 to over USD 44 billion by 2032, reflecting a compound annual growth rate (CAGR) close to 80%. While specific figures vary, the trend points towards a dramatic expansion from the current negligible base.

A key trend is the development of GW-scale green ammonia projects primarily targeting export markets. These projects aim to leverage locations with superior renewable resources to produce ammonia as a transportable, low-carbon energy carrier or feedstock for international markets.

Policy support is a critical enabler for this anticipated growth. However, realizing these growth projections hinges on converting the large pipeline of announced projects into operational assets. The significant contribution projected from blue ammonia (SMR/ATR + CCS) by 2030 according to AEA data[78] suggests that this pathway will play a major role alongside green ammonia in decarbonizing the sector this decade. The final mix and total capacity achieved by 2030 remain uncertain due to the prevailing economic and commercial hurdles facing many projects.

6.3 | Key Drivers and Hurdles for Commercialization

The push towards green and low-emission ammonia is propelled by several strong drivers, but faces equally significant hurdles.

a. **Drivers:**

  i. **Decarbonization Goals:** Overarching national and international climate targets (e.g., Paris Agreement, net-zero commitments) necessitate deep emissions reductions in hard-to-abate sectors like ammonia production.

[75] ammoniaenergy.org, accessed April 10, 2025

[76] Ammonia Energy Association, accessed April 10, 2025

[77] Technology status: ammonia production from electrolysis-based hydrogen, accessed April 10, 2025

[78] Ammonia Energy Association, accessed April 10, 2025

ii. **Policy Support:** Government incentives, subsidies (like IRA tax credits), mandates (like EU RFNBO quotas), and carbon pricing mechanisms are crucial for improving the economic viability of low-emission ammonia.

iii. **New Market Opportunities:** The potential use of low-carbon ammonia as a maritime fuel, a means for power generation (co-firing or dedicated turbines/fuel cells), and an efficient carrier for transporting hydrogen opens up vast new demand potential beyond traditional fertilizer and industrial uses.

iv. **Energy Security and Independence:** Green ammonia produced from domestic renewable resources offers a pathway to reduce reliance on volatile global fossil fuel markets and enhance energy supply security.

b. Hurdles:

i. **Cost Competitiveness:** Green Ammonia is currently significantly more expensive than conventional grey ammonia (cost premiums cited range from 40% to over 120%, potentially even higher). Blue ammonia also carries a cost premium over grey.

ii. **High Capital Costs:** Large-scale green ammonia projects require massive upfront investment in renewable energy generation (solar, wind farms) and electrolyzer capacity.

iii. **Renewable Energy Supply:** Securing access to vast quantities of low-cost, reliable renewable electricity is paramount.

iv. **Intermittency Management:** Integrating variable renewable energy sources with ammonia production requires costly solutions like energy storage or flexible operation capabilities.

v. **Technology Scaling and Manufacturing:** Ramping up electrolyzer manufacturing to meet multi-GW demand and ensuring the reliability and efficiency of large-scale systems are ongoing challenges.

vi. **Infrastructure Development:** New infrastructure is needed for transporting, storing, and utilizing ammonia in emerging applications (e.g., ship bunkering facilities, ammonia cracking plants to release hydrogen).

vii. **Securing Offtake Agreements:** Finding buyers willing to commit to long-term contracts at prices sufficient to cover production costs is a major barrier to project financing.[33]

viii. **Downstream Environmental Impacts:** Managing potential NO_x and N_2O emissions when ammonia is used as a fuel is an environmental challenge that requires technological solutions (e.g., advanced combustion systems, catalysts).

ix. **Water Availability:** Electrolysis requires significant amounts of water, which could be a constraint in water-scarce regions suitable for solar/wind deployment.

Overall, the transition is strongly motivated by climate policy and the promise of new markets. However, economic viability remains the most critical hurdle. Overcoming the substantial cost gap compared to incumbent grey ammonia production and securing firm, long-term demand willing to absorb this green premium are the most pressing near-term challenges that will determine the pace of large-scale commercial deployment.

7| CONCLUSION AND SYNTHESIS

The global ammonia industry stands at a pivotal juncture. Conventional grey ammonia production, built on mature fossil fuel-based technologies like SMR, remains the dominant force, supplying nearly all of the world's ~150 Mtpa demand from large-scale plants concentrated in fossil-rich regions. However, its significant carbon footprint is increasingly misaligned with global climate objectives.

Green ammonia, produced via renewable-powered electrolysis, offers a pathway to near-zero production emissions. Yet, despite its environmental advantages, its commercial penetration is currently negligible, estimated at less than 0.1% of the global market as of late 2024. Operational green ammonia capacity consists primarily of small-scale pilot and demonstration projects, often integrated into existing conventional facilities.

A clear geographical divergence is emerging. While conventional production is tied to fossil fuel reserves, the future of green ammonia appears linked to regions with abundant renewable energy resources, such as Australia, the Middle East, North Africa, Chile, and parts of North America. This shift holds the potential to reshape global energy trade flows but requires substantial investment in new production and logistical infrastructure. Furthermore, green ammonia's modular nature offers potential for decentralized production closer to end-users, complementing large export hubs.

Comparing the technologies highlights stark contrasts. Conventional ammonia leverages decades of optimization and economies of scale, resulting in lower costs but high emissions. Green ammonia promises environmental benefits but faces challenges related to higher costs (driven by electricity prices and electrolyzer CAPEX), the integration of developing electrolysis technology, and managing the intermittency of renewable power sources. Blue ammonia, using SMR with CCUS, presents an intermediate option, reducing emissions significantly while leveraging existing assets, and is projected to play a substantial role in the near-term transition alongside green ammonia.

The future growth potential for low-emission ammonia is immense, evidenced by a pipeline of announced projects totaling hundreds of millions of tonnes in ambition. This ambition is fueled by decarbonization mandates, supportive policies, and the prospect of new large-scale markets in shipping and power. However, converting this potential into operational capacity faces formidable hurdles. The high cost premium over grey ammonia, the difficulty in securing long-term bankable offtake agreements, and the sheer scale of investment required for GW-scale renewable and electrolysis deployment are major barriers that have slowed progress beyond the initial flagship projects.

In conclusion, green ammonia is poised for significant growth from its current nascent state. Its trajectory towards becoming a major component of the global ammonia supply, however, is not guaranteed and depends critically on continued technological innovation (particularly in electrolysis), sustained and effective support to bridge the economic gap, and the successful development and scaling of new demand sectors willing and able to absorb the associated green premium. The coming decade will be crucial in determining whether green ammonia can overcome its challenges and fulfill its potential as a key enabler of a decarbonized energy and agricultural future, likely progressing alongside substantial deployment of blue ammonia as part of a multifaceted industry transition.

SECTION 2:

Lock-in Risk Analysis for Green and Low-Carbon Ammonia Production Activities

1| INTRODUCTION

Technology lock-in, within the context of climate change mitigation, describes a situation where investments in particular technologies, especially those involving long-lived infrastructure, create path dependencies that perpetuate their use, thereby hindering or delaying the transition towards lower-carbon or ultimately zero-carbon alternatives. This phenomenon is particularly pertinent to energy systems, where infrastructure such as power plants, pipelines, and industrial facilities often have operational lifetimes spanning decades. Such long-term commitments can inadvertently obstruct the achievement of long-term climate objectives, such as those enshrined in the Paris Agreement, which aims to limit global warming well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. The potential for carbon lock-in underscores the critical need to evaluate new energy investments not only for their immediate emissions profile but also for their compatibility with deep decarbonization pathways extending to mid-century and beyond.

The objective of this Section is to conduct a formal analysis of potential lock-in risks associated with the global deployment of various low-carbon ammonia production technologies. This analysis is framed specifically considering the requirements of GS4GG methodology for Green Ammonia Production as per the standard governing the demonstration of additionality under Requirements for additionality demonstration, explicitly mandates an assessment of lock-in risk as part of the additionality determination (Section 6.2). Methodologies developed under GS4GG must ensure that credited activities avoid locking in levels of emissions, technologies, or carbon-intensive practices that are incompatible with the long-term goals of the Paris Agreement and the principles of the mechanism, such as encouraging ambition over time.

The relevance of this analysis stems from the rapidly growing interest and investment in low-carbon ammonia. Ammonia (NH_3) is increasingly viewed as a key enabler for decarbonization across multiple sectors, including its traditional use in fertilizers, as a potential zero-carbon fuel for maritime transport, and as an efficient carrier for hydrogen energy.[79] This burgeoning demand is driving a significant global expansion of planned production capacity, utilizing various "low-carbon" pathways.[80] However, the concept of "lock-in" is not confined to the dichotomy between fossil fuels and renewables; it is equally relevant *within* the portfolio of low-carbon technologies themselves. Transitional solutions, such as "blue" ammonia (produced from fossil fuels with carbon capture), while offering lower emissions than conventional "grey"

[79] Low-Carbon Ammonia Certification—Discussion Paper, accessed May 2, 2025

[80] Low-Emission Ammonia Data (LEAD): Plants Executive Summary, accessed May 2, 2025

ammonia, still involve long-lived fossil-based infrastructure and residual emissions.[81] The explicit inclusion of lock-in analysis within the Article 6 framework signals the necessity to scrutinize *all* proposed mitigation activities, irrespective of their "low-carbon" label, for their long-term compatibility with ambitious climate targets. Given the substantial investments flowing into the low-carbon ammonia sector and the long operational lifetimes of the associated infrastructure, a proactive assessment of lock-in risks is crucial *before* large-scale deployment potentially creates irreversible pathways that could compromise mid-century climate goals. [82]

This analysis covers the primary low-carbon ammonia production pathways currently being pursued – namely green ammonia produced via water electrolysis using renewable energy, and for comparison also includes blue ammonia produced via natural gas reforming coupled with carbon capture, utilization, and storage (CCUS). Emerging pathways like turquoise ammonia (methane pyrolysis) are also considered where relevant. The assessment examines activities across key geographical regions exhibiting significant development interest, including the United States, the European Union, Australia, Chile, the Middle East and North Africa (MENA), and parts of Asia. The evaluation is conducted against the specific lock-in criteria derived from the GS4GG standard Requirements for methodology development and Requirements for additionality demonstration.

It is important to note that this methodology explicitly excludes ammonia production using hydrogen derived from fossil fuels, including processes like Steam Methane Reforming (SMR), Autothermal Reforming (ATR), or coal gasification, irrespective of whether Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU) technologies are employed (i.e., pathways commonly referred to as "grey," "brown," or "blue" ammonia are excluded).

2| GLOBAL LANDSCAPE OF LOW-CARBON AMMONIA PRODUCTION

The transition towards a low-carbon economy has spurred significant interest in alternative methods for producing ammonia, a foundational chemical commodity. Traditionally produced via carbon-intensive processes, ammonia manufacturing is now seeing the emergence and scaling-up of pathways designed to drastically reduce its greenhouse gas (GHG) footprint.

2.1 | Overview of Production Pathways

Several distinct routes for producing low-carbon ammonia are being developed and deployed globally:

[81] miq.org, accessed May 3, 2025

[82] Low-Emission Ammonia Data (LEAD): Plants Executive Summary, accessed May 2, 2025

a. **Green Ammonia:** This pathway aims for near-zero GHG emissions during production by utilizing renewable energy sources.[83] The core process involves:

   i. *Hydrogen Production:* Water electrolysis (splitting H_2O into H_2 and O_2) powered by renewable electricity (e.g., solar PV, wind, hydropower). Various electrolyzer technologies exist, including Alkaline Water Electrolysis (AEL), Proton Exchange Membrane (PEM) electrolysis, Solid Oxide Electrolysis Cells (SOEC), and Anion Exchange Membrane (AEM) electrolysis, each with different operational characteristics, efficiencies, and costs.[84]

   ii. *Nitrogen Production:* Nitrogen (N_2) is typically obtained from ambient air using an Air Separation Unit (ASU), which itself is powered by renewable electricity.

   iii. *Ammonia Synthesis:* The green hydrogen and nitrogen are then combined under high pressure and temperature using a catalyst in the Haber-Bosch (HB) synthesis loop ($N_2+3H_2 \leftrightarrow 2NH_3$). While chemically identical to conventional ammonia, the "green" designation refers to the renewable inputs and power source.[85]

b. **Blue Ammonia:** This pathway seeks to reduce the emissions associated with conventional ammonia production by integrating carbon capture technology. It involves:

   i. *Hydrogen Production:* Hydrogen is produced from natural gas (methane, CH_4) using either Steam Methane Reforming (SMR) or Autothermal Reforming (ATR). These processes inherently generate significant CO_2 emissions.

   ii. *Carbon Capture:* Carbon Capture, Utilization, and Storage (CCUS) technologies are applied to capture a substantial portion (typically targeting >90%) of the CO_2 generated during hydrogen production. The captured CO_2 is then either utilized in other industrial processes or permanently stored underground.

   iii. *Ammonia Synthesis:* The resulting "blue" hydrogen is combined with nitrogen (often sourced implicitly from air used in the reforming process, especially ATR) in the Haber-Bosch loop. Blue ammonia significantly reduces direct process emissions compared to grey ammonia but does not eliminate them entirely, and its overall climate benefit is highly dependent on the capture rate achieved and,

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[83] Ammonia: zero-carbon fertiliser, fuel and energy store - Royal Society, accessed May 2, 2025

[84] Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025,

[85] Driving sustainability through green ammonia production - Endress+Hauser, accessed May 2, 2025

critically, on mitigating upstream methane emissions from the natural gas supply chain.

c. **Turquoise Ammonia:** This emerging pathway involves methane pyrolysis, where natural gas is decomposed into hydrogen gas and solid carbon using high temperatures, potentially supplied by renewable electricity.[86]

  i. $CH_4 \rightarrow C(s) + 2H_2$ The hydrogen produced can then be used in the Haber-Bosch process. This route avoids direct CO_2 emissions from hydrogen production, but its viability depends on the energy source used for pyrolysis and the effective management (e.g., sequestration or utilization) of the solid carbon co-product. Its technological readiness level is currently lower than green or blue pathways.

d. **Novel/Alternative Methods:** Research is ongoing into fundamentally different ammonia synthesis methods that could potentially operate under milder conditions (lower temperature and pressure) or bypass the Haber-Bosch process altogether. Examples include direct electrochemical nitrogen reduction (NRR), plasma-assisted synthesis, and biological nitrogen fixation pathways.[87] While promising for future efficiency gains and decentralization, these technologies are generally at earlier stages of development (lower Technology Readiness Levels, TRLs) compared to electrolysis or SMR/ATR-based routes.

2.2 | Geographical Distribution and Scale

The global landscape for low-carbon ammonia is characterized by rapidly increasing project announcements and significant policy support across multiple regions. The Ammonia Energy Association (AEA) tracked 485 announced low-emission ammonia projects (representing 596 phases of expansion) by February 2025, totaling a potential capacity of 451.2 million tonnes (MT), a dramatic increase from 103 projects in December 2022.[88] Key geographical hotspots include:

a. **United States[89]:** A surge in project activity is driven by the Inflation Reduction Act (IRA), offering substantial production tax credits (PTC) like 45V for clean hydrogen (up to $3/kg for lowest lifecycle emissions) and extending the 45Q tax credit for CCUS. The Bipartisan Infrastructure Law (BIL) allocated $7 billion for the Regional Clean Hydrogen Hubs (H2Hubs) program to stimulate integrated production, infrastructure, and consumption. Consequently, both blue ammonia projects (leveraging existing natural gas infrastructure and CCUS incentives, e.g., Wabash Valley Resources, Mosaic Faustina, and the Appalachian Regional Clean Hydrogen Hub ($ARCH_2$)) and green ammonia projects (leveraging renewable resources

[86] Monolith Materials - Ammonia Energy Association, accessed May 2, 2025,
[87] Low-Carbon Ammonia Technology: Blue, Green, and Beyond - RMI, accessed May 2, 2025
[88] Low-Emission Ammonia Data (LEAD): Plants Executive Summary, accessed May 2, 2025,
[89] US Department of Energy, accessed May 2, 2025,

and the 45V PTC) are being pursued.[90] The US aims for 10 MMT/year of clean hydrogen production by 2030, rising to 50 MMT/year by 2050.[91]

b. **European Union:** The EU's ambitions are driven by climate targets (Fit for 55 package aiming for 55% GHG reduction by 2030) and energy security concerns (REPowerEU plan).[92] REPowerEU doubled the EU's 2030 hydrogen target to 20 MMT/year (10 MMT domestic production, 10 MMT imports). Policies include binding targets for Renewable Fuels of Non-Biological Origin (RFNBOs) in transport and industry under the revised Renewable Energy Directive (RED III), the European Hydrogen Bank to provide financial support via auctions, and the Important Projects of Common European Interest (IPCEI) program to fund large-scale projects across the value chain. The primary focus is on green hydrogen and its derivatives (like ammonia) for both domestic production and import, with initiatives like Germany's H_2Global specifically tendering for green ammonia imports.[93]

c. **Australia:** Possessing abundant solar and wind resources, Australia aims to be a global leader in green hydrogen production and export.[94] The 2024 National Hydrogen Strategy sets targets for production (0.5 MMT/yr by 2030, 15 MMT/yr by 2050) and exports (0.2 MMT/yr by 2030). Key support mechanisms include the $2 billion Hydrogen Headstart program providing production credits, a legislated Hydrogen Production Tax Incentive ($2/kg refundable offset), ARENA funding for R&D and deployment, and the development of a Guarantee of Origin (GO) scheme.[95] Focus areas include exports (to Asia and Europe, e.g., Germany deal) and domestic use in green metals (iron, alumina) and ammonia production. Australia boasts the largest announced pipeline of hydrogen projects globally.[96]

d. **Chile:** Leveraging exceptional solar potential in the Atacama Desert and strong winds in the south, Chile's National Green Hydrogen Strategy (2020) aims to produce the world's cheapest green hydrogen (<$1.5/kg by 2030) and become a top-three exporter by 2040.[97] Targets include 5 GW of electrolysis capacity under development by 2025 and 25 GW by 2030.[98]

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[90] Stimulating Clean Hydrogen Demand: The Current Landscape - Belfer Center, accessed May 3, 2025

[91] U.S. National Clean Hydrogen Strategy and Roadmap, accessed May 3, 2025

[92] Hydrogen - Energy - European Commission, accessed May 3, 2025

[93] The role of hydrogen in a future, low- carbon, and secure European energy system - Renewables Grid Initiative, accessed May 3, 2025

[94] What is Australia's National Hydrogen Strategy? - AZoCleantech, accessed May 3, 2025

[95] National Hydrogen Strategy 2024 - DCCEEW, accessed May 3, 2025,

[96] Growing Australia's hydrogen industry - DCCEEW, accessed May 3, 2025,

[97] Chile: Current Status of Green Hydrogen, Coal Exit and Climate Resilience - Chilean-German Energy Partnership, accessed May 3, 2025

[98] Chiles National Green Hydrogen Strategy | Internationale Klimaschutzinitiative (IKI), accessed May 3, 2025

Green hydrogen is identified as a key sector for achieving Chile's climate goals (carbon neutrality by 2050) and NDCs, potentially contributing 21-27% of the required emissions reductions. Pilot projects like Haru Oni (producing e-fuels) are operational, though scaling up to meet the large number of announced projects faces investment hurdles.

e. **MENA Region (Saudi Arabia, UAE, Oman):** These nations view low-carbon hydrogen (both blue and green) as crucial for economic diversification away from oil and gas and for meeting their own net-zero targets (e.g., UAE/Oman by 2050, Saudi Arabia by 2060).[99] Leveraging abundant solar resources and existing energy infrastructure, they are developing national hydrogen strategies and launching large-scale projects, primarily targeting exports. Examples include Saudi Arabia's NEOM green hydrogen/ammonia project and the UAE's target to capture 25% of the global low-carbon hydrogen market by 2030.[100] Hydrogen development is explicitly linked to their NDCs.[101]

f. **Asia (Japan, South Korea, China):** These represent major potential demand centers. Japan's strategy, for instance, envisions importing significant quantities of low-carbon ammonia (potentially 100 MT/year regionally by 2050) for co-firing in power plants and use as shipping fuel. [102] South Korea is also pursuing ammonia for power generation and shipping. China has vast potential for domestic production leveraging its renewable resources and manufacturing capabilities. These countries are actively seeking international partnerships and developing domestic technologies.[103]

The global scale-up is significant, but faces challenges. While the project pipeline is large, moving projects from announcement to Final Investment Decision (FID) has been slower than anticipated, often due to lack of firm offtake agreements and cost uncertainties.[104]

2.3 | Policy Drivers & Market Context

The development of low-carbon ammonia is intrinsically linked to national and international climate policies. Nationally Determined Contributions (NDCs) submitted under the Paris Agreement, and increasingly, Long-Term Low Emission Development Strategies (LT-LEDS), provide the overarching framework and national context for decarbonization efforts, often identifying roles for hydrogen and its derivatives. These

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[99] Commitments and Contradictions: Gulf and Middle East Decarbonization Strategies Ahead of COP28 - Center on Global Energy Policy at Columbia University SIPA | CGEP %, accessed May 3, 2025

[100] The Future of Hydrogen in the GCC Countries - Gulf Research Center, accessed May 3, 2025,

[101] Hydrogen in The Arabian Gulf Countries, accessed May 3, 2025

[102] Ammonia Energy Association, accessed May 2, 2025

[103] Monolith Materials - Ammonia Energy Association, accessed May 2, 2025

[104] Low-Emission Ammonia Data (LEAD): Plants Executive Summary, accessed May 2, 2025

national strategies, however, are influenced by specific resource endowments (e.g., renewable potential vs. existing gas infrastructure) and economic priorities, leading to different technological focuses across regions. For instance, the US IRA's structure potentially supports both green and blue pathways depending on lifecycle emissions accounting, while the EU's REPowerEU emphasizes renewable hydrogen. This policy-technology nexus creates a heterogeneous global landscape rather than a uniform shift towards a single low-carbon ammonia solution. The established grey ammonia industry benefits from significant economies of scale achieved over decades, with large, centralized SMR plants dominating production. New green ammonia projects, often linked to specific, potentially smaller-scale renewable energy installations, may struggle to compete initially. Blue ammonia, conversely, can often leverage existing SMR infrastructure and operational expertise through retrofits or co-location, potentially offering a faster route to large-scale, lower-emission production. This incumbency advantage for blue ammonia could inadvertently slow the deployment of green ammonia, even if green pathways offer superior long-term climate alignment, thereby representing a potential lock-in risk that policy frameworks must carefully consider.

3| METHODOLOGY FOR LOCK-IN RISK ASSESSMENT

3.1 | Principles & requirements

This section outlines the methodology followed for low-carbon ammonia production activities to assess technology lock-in – in particular assessed against the specific criteria outlined in the GS4GG's standard Requirements for additionality demonstration, Section 6.2, "Lock-in risk analysis". This standard requires that GS4GG methodologies ensure activities avoid lock-in. The assessment considers the following key factors derived from the standard:

a. Compatibility with the long-term goals of the Paris Agreement.
b. Consistency with the host country's Long-Term Low Emission Development Strategy (LT-LEDS), where submitted.
c. Utilization of technology with the lowest feasible greenhouse gas intensity for long-lifetime investments, considering regional context.
d. Avoidance of inefficient use of resources critical for climate change mitigation or other policy objectives.
e. Consideration of socio-economic contexts, existing infrastructure, and path dependencies.
f. The technical or operational lifetime of the technologies or practices.
g. The emissions intensity of these technologies and practices.
h. The scale of the activity.
i. The availability and feasibility of alternative options given national circumstances.

j. Potential exemption from detailed analysis for technologies with lifetimes ≤ 10 years.

The analysis adopts a neutral approach regarding technology and source, while acknowledging that Gold Standard methodology is **not applicable** to project activities involving ammonia production using hydrogen derived from fossil fuels, including processes like Steam Methane Reforming (SMR), Autothermal Reforming (ATR), or coal gasification, irrespective of whether Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU) technologies are employed (i.e., pathways commonly referred to as "grey," "brown," or "blue" ammonia are excluded).

A particular focus of the assessment is to lock in risks to identify by assessing whether the project [2]:

- **Creates dependency on fossil fuels:** This criterion scrutinizes whether the project design, even if primarily low-carbon, necessitates or encourages continued reliance on fossil fuels for its operation, including for backup systems or auxiliary processes.
- **Extends the lifespan of high-emission infrastructure:** This addresses situations where investments might retrofit or prolong the operational life of existing carbon-intensive assets (e.g., coal plants) instead of promoting their replacement with truly low-carbon alternatives.
- **Adopts technologies with no decarbonization pathway:** This refers to irreversible design choices or technological selections that would inherently hinder or prevent future, deeper decarbonization efforts over the project's lifespan.
- **Triggers market/regulatory shifts favoring fossil fuels:** This criterion ensures that the project does not inadvertently crowd out renewable energy solutions or create market dynamics that disincentivize the broader transition away from fossil fuels.

3.2 | Process to Identify Lock-in Emissions Risks (Stepwise Approach)

The process followed for identifying and mitigating lock-in risks includes:

- **Project Component Analysis:** Each individual component of the project activity must be evaluated for its potential lock-in risks, with specific mitigation strategies identified for each.
  - **Electrolysis Technology:** The assessment considers if electrolyser, powered by renewable energy, are modular and allow for upgrades, ensuring no fossil dependency and scalability.
  - **Dispatchable RE Source:** Renewable energy sources (e.g., solar, wind with storage) must be evaluated to ensure they avoid any need for fossil backup. Mitigation involves the use of battery to ensure a 24/7 renewable energy supply.
  - **Grid Interconnection:** If the project is grid-tied, it must be assessed to ensure no reliance on fossil-dominated grids. Mitigation can be achieved

through an off-grid design or the use of 100% renewable energy-certified grid electricity.

- **Auxiliary Systems:** Hydrogen storage and transport systems must utilize zero-emission methods. Mitigation requires avoiding methane-based compressors or pipelines.

- **Comparison to Baseline (BAU):** The project scenario is compared against a Business-as-Usual (BAU) baseline. The BAU scenario typically involves fossil-based ammonia production (e.g., coal/SMR plants) with long lifespans (30–40 years). The project scenario, involving electrolysis and renewable energy systems, should ideally have a shorter lifespan (20–25 years) and no fossil linkages.
- **Qualitative Checklist:** The project must confirm it meets all criteria for lock-in avoidance through a qualitative checklist: no fossil fuel combustion in any process, renewable energy infrastructure is modular and upgradable preventing stranded assets, no long-term contracts for fossil-based inputs (e.g., gas pipelines), and compliance with national net-zero pathways (e.g., alignment with the host country's 2050 targets).

4| LOCK-IN RISK ANALYSIS FOR GREEN AMMONIA PRODUCTION FACILITIES

4.1 | Technology Lifetimes and Compatibility with Long-Term Goals

The operational lifetime of the infrastructure associated with ammonia production is a primary determinant of lock-in risk. Long-lived assets installed today commit capital and potentially emissions for decades, influencing future investment decisions and potentially hindering alignment with evolving climate targets. Based on available information, typical operational lifetimes for key components are estimated as follows:

a. Electrolyzer: The lifetime varies significantly by type and operating conditions.

i. *Alkaline (AEL):* Generally considered durable with long system lifetimes (potentially decades with maintenance), though stack replacement is still required. Stack lifetimes might exceed 80,000 hours (approx. 9 years continuous) [105].

ii. *PEM:* Stack lifetimes are generally shorter than AEL due to membrane/electrode wear, potentially in the 3.5 to 11.5-year range (approx. 30,000-100,000 hours).[106] System lifetime depends on stack replacement strategy.

iii. *SOEC:* Historically faced challenges with degradation due to high temperatures (lifetimes < 2.3 years cited by IRENA in 2020[107]). However, manufacturers like Bloom Energy now target system lifetimes of 5+ years,

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[105] Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025

[106] PEM Electrolysers vs. Alkaline Electrolysers. - Stargate Hydrogen, accessed May 3, 2025

[107] Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025

with stack replacement potentially around 40,000 hours (approx. 4.5 years continuous).[108] Continuous operation ("hot standby") is key to longevity.

iv. *AEM:* Still emerging, lifetimes are less certain but potentially shorter than AEL/PEM initially.[109]

b. **Air Separation Units (ASUs):** These are robust industrial units, typically part of large chemical complexes. While specific lifetime data is scarce in the provided material, industrial gas facilities generally operate for several decades (e.g., 20-40 years), suggesting ASUs are long-lived assets.[110]

c. **Haber-Bosch (HB) Synthesis Loop:** The core HB process equipment (reactors, compressors, heat exchangers) represents mature, capital-intensive industrial technology designed for continuous operation over long periods, typically 20 years or more.[111] Frequent thermal cycling (start-ups/shut-downs) can damage catalysts and equipment, reinforcing the design for longevity under stable conditions.

d. **Carbon Capture, Utilization, and Storage (CCUS) Equipment:** CCS facilities integrated with SMR/ATR plants are expected to have lifetimes commensurate with the industrial plants they serve, likely 20+ years.

Table 5: Estimated Operational Lifetimes of Key Low-Carbon Ammonia Production Components

Component	Type	Estimated Lifetime Range	Key Factors Influencing Lifetime
Electrolyzer System	Alkaline (AEL)	>5 years, potentially decades	Maintenance, operating conditions
	PEM	Variable, depends on stack replacement	Stack degradation, operating cycles
	SOEC	>5 years (target)	Operating temperature, "hot standby" mode, degradation rate
	AEM	Emerging, TBD	Membrane stability, operating conditions
Electrolyzer Stack	Alkaline (AEL)	>80,000 hours (~9 years)	Electrode/membrane stability
	PEM	30,000-100,000 hours (~3.5-11.5 yrs)	Membrane/catalyst degradation, cycling
	SOEC	~40,000 hours (~4.5 years)	High temperature degradation, material stability
	AEM	Emerging, TBD	Membrane stability
Air Separation Unit (ASU)	Cryogenic/PSA	Decades (e.g., 20-40 years)	Industrial standard, maintenance

108 Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025

109 Demystifying Electrolyzer Production Costs - Center on Global Energy Policy, accessed May 3, 2025

110 Safe green ammonia production - Endress+Hauser, accessed May 3, 2025,

111 Power to Ammonia: alternative synthesis technologies - Ammonia ..., accessed May 3, 2025

Haber-Bosch Synthesis Loop	Standard	>20 years	Designed for continuous operation, catalyst life, material integrity
CCUS Equipment	Various	>20 years	Integration with host plant, material durability Assumed based on industrial plant lifetimes

Note: Lifetimes are estimates and can vary based on specific design, operation, and maintenance practices.

4.2 | Assessing compatibility with long-term Paris Agreement goals[112]:

a. **Green Ammonia:** The physical infrastructure (electrolyser, ASUs, HB loop) involves components with lifetimes potentially extending well beyond 2050. While *operationally* compatible with net-zero if powered exclusively by zero-carbon renewable energy, the long asset life raises considerations. Does investing heavily in dedicated ammonia infrastructure preclude potentially more efficient future energy pathways? Does it rely on sustained availability of vast renewable resources? The 10-year lifetime exemption for avoiding lock-in analysis under is unlikely to apply to entire green ammonia production facilities, given the multi-decade lifespan of core components like ASUs and HB loops. However, the shorter stack lifetimes for some electrolyzer types (PEM, SOEC) offer potential for technological upgrades during the plant's operational period. This modularity in the hydrogen production unit could mitigate lock-in risk compared to fully integrated systems, provided the balance of plant allows for such upgrades.

b. **Blue Ammonia:** SMR/ATR plants coupled with CCS represent significant long-term investments in fossil fuel-based infrastructure, with typical lifetimes exceeding 20 years.[113] This timeline presents a direct conflict with the trajectory required for a 1.5°C or well-below 2°C world, which necessitates a rapid phase-out of unabated fossil fuel use well before 2050. Investing in new blue ammonia facilities today risks creating assets that are misaligned with climate goals for a substantial portion of their operational life. This could lead to either premature retirement and stranded assets or continued operation contributing to residual GHG emissions (from imperfect capture and upstream leakage) that are incompatible with net-zero targets. This pathway therefore carries a high risk of technological and emissions lock-in.

c. **Turquoise Ammonia:** Similar to blue ammonia, this pathway relies on natural gas feedstock and involves long-lived plant infrastructure. Its compatibility depends on using zero-carbon energy for the pyrolysis process and ensuring the long-term, verifiable sequestration or sustainable use of

[112] Chapter 6: Energy systems - IPCC, accessed May 2, 2025,

[113] events.engineering.oregonstate.edu, accessed May 3, 2025

the solid carbon produced. The reliance on fossil gas feedstock still presents a lock-in risk related to continued fossil fuel extraction and infrastructure.

4.3 | Greenhouse Gas Intensity

The GHG intensity of the produced ammonia is a crucial factor in assessing lock-in risk, particularly concerning the A6.4 criterion requiring the use of technologies with the "lowest greenhouse gas intensity" feasible in the relevant region for long-lifetime investments. Comparing the lifecycle GHG intensity across pathways requires careful consideration of system boundaries, GWP metrics (e.g., AR5 vs. AR6), and the inclusion of upstream and embodied emissions.

a. **Grey Ammonia (SMR without CCS):** Serves as the baseline for comparison. Cradle-to-gate lifecycle assessments typically report intensities around 2.6 to 2.9 kg CO_2e/kg NH_3.[114] Process emissions reported under specific regulatory frameworks (like IPCC Tier 1 or EPA GHGRP) may differ based on boundaries; for example, the IPCC 2006 default factor for modern European SMR plants (including fuel and feedstock) is 1.694 t CO_2/t NH_3[115], while an EPA factor cited for process emissions only was 1.2 t CO_2/t NH_3.[116]

b. **Blue Ammonia (SMR/ATR + CCS):** GHG intensity is highly variable. Key factors include the CO_2 capture rate (typically 90-98% targeted for the process emissions), the energy source used for the capture process, and, critically, upstream methane emissions from the natural gas supply chain.

   i. Studies report cradle-to-gate values ranging from approximately 0.4 kg CO_2e/kg NH_3 (assuming 95% capture and very low upstream methane leakage via certified gas) to 0.7-1.4 kg CO_2e/kg NH_3 under less optimistic assumptions.[117]

   ii. A Well-to-Wake (WtW) assessment for maritime fuel use estimated blue ammonia emissions at 83 ± 12 gCO_2e/MJ in 2025, falling to 29 ± 4 gCO_2e/MJ by 2050 with technology improvements (ATR, 98% capture) and grid decarbonization, but still struggling to meet stringent low-carbon fuel thresholds primarily due to upstream methane.[118]

   iii. The significant impact of upstream methane leakage cannot be overstated. Analysis suggests methane leaks can contribute ~0.4 kg CO_2e/kg NH_3 to the baseline SMR pathway, potentially dwarfing the

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[114] miq.org, accessed May 3, 2025

[115] www.ipcc-nggip.iges.or.jp, accessed May 2, 2025

[116] Technical Support Document for the Ammonia Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases - Environmental Protection Agency (EPA), accessed May 2, 2025

[117] miq.org, accessed May 3, 2025

[118] https://www.ifpenergiesnouvelles.fr/sites/ifpen.fr/files/inline-images/20250310_IFPEN_CMACGM_ok.pdf, accessed May 3, 2025

direct process emissions remaining after high CCS capture rates.[119] This makes robust measurement, reporting, verification (MRV), and mitigation of upstream methane absolutely critical for blue ammonia to deliver credible climate benefits and avoid locking in significant GHG emissions.

c. **Green Ammonia (Electrolysis + Renewables):** Ideally produces near-zero operational emissions if powered by 100% renewable electricity.[120] However, a full lifecycle perspective must account for:

   i. *Carbon Intensity of Electricity:* Grid-connected electrolysis will reflect the grid's carbon intensity unless strict additionality, temporal correlation, and geographic correlation criteria are met. [121] Dedicated renewable power is assumed for "green" designation.

   ii. *Embodied Emissions:* Manufacturing and deploying renewable energy infrastructure (solar panels, wind turbines, hydropower dams) and the ammonia plant itself carries an embedded carbon footprint.[122]

   iii. Reported LCA values vary widely based on the renewable source and inclusion of embodied emissions

      i. The GH2 Green Ammonia Protocol sets a threshold of ≤ 0.3 kg CO_2e/kg NH_3 (average over 12 months), covering key production steps but excluding embodied emissions from infrastructure.[123]

      ii. LCA studies including embodied emissions show significant variation: Hydropower-based ammonia is estimated around 0.34-0.38 kg CO_2e/kg NH_3.[124] Wind-based ammonia can be lower (implied <0.3 kg CO2e/kg NH_3 based on H_2 values[125]). Solar PV-based ammonia can be significantly higher (e.g., ~0.51 kg CO_2e/kg NH_3[126]), due to the higher embodied emissions of PV panels compared to wind or hydro per kWh generated. Nuclear-based pathways show very low embodied emissions.

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[119] miq.org, accessed May 3, 2025

[120] Green ammonia - Iberdrola, accessed May 2, 2025

[121] Green ammonia - Iberdrola, accessed May 2, 2025

[122] Considering Embodied Greenhouse Emissions of Nuclear and and Renewable Power Plants for Electrolytic Hydrogen and Its Use for Synthetic Ammonia, Methanol, Fischer–Tropsch Fuel Production, accessed May 3, 2025

[123] gh2.org, accessed May 3, 2025

[124] Comparative life cycle assessment of various ammonia production methods, accessed May 3, 2025

[125] gh2.org, accessed May 3, 2025

[126] gh2.org, accessed May 3, 2025

iv. This variability within "green" ammonia highlights that the choice of renewable source matters significantly for the actual lifecycle emissions.

d. Fugitive Emissions (H_2, N_2O): Beyond CO_2, other GHGs require consideration.

i. *Nitrous Oxide (N_2O):* A potent GHG (GWP ~273-298 over 100 years[127] potentially emitted during the Haber-Bosch process itself, or more significantly, during the downstream production of certain fertilizers (like ammonium nitrate) or from ammonia combustion/use as fuel.[31] Mitigation technologies exist (e.g., catalysts for N_2O abatement in nitric acid plants, engine tuning for fuel use[128]), but require careful implementation and monitoring.

ii. *Hydrogen (H_2):* Fugitive hydrogen emissions are an emerging concern. While not a direct GHG, H_2 reacts in the atmosphere to indirectly increase the lifetime and warming effect of methane and ozone.[129] Robust monitoring and leak prevention protocols are needed across the hydrogen value chain (production, storage, transport, use), but standardized methodologies are still developing.[130]

iii. Accurate and transparent accounting for these non-CO_2 GHGs is essential for credible GHG intensity calculations and ensuring environmental integrity.

Table 6:Comparative Life Cycle GHG Intensity of Ammonia Production Pathways

Pathway	Typical GHG Intensity Range (kg CO_2e/kg NH_3)	Key Assumptions / Notes	Relevant Sources
Grey SMR (No CCS)	~1.7 - 2.9	Cradle-to-gate or process+fuel. Varies with boundary, region, plant efficiency.	131
Blue SMR/ATR + CCS (90-95% capture)	~0.4 - 1.4	Cradle-to-gate. Highly sensitive to capture rate AND upstream methane emissions. Lower end requires certified low-leakage gas.	
Green Electrolysis (Hydropower)	~0.34 - 0.38	LCA including embodied emissions.	132

[127] Emission Factors for Greenhouse Gas Inventories, accessed May 2, 2025

[128] Ammonia Energy Conference 2024: Ammonia for Maritime Propulsion is full speed ahead!, accessed May 2, 2025

[129] Policy Brief: A sustainable hydrogen strategy for the EU - European Environmental Bureau (EEB), accessed May 3, 2025

[130] Compendium of Greenhouse Gas Emissions Estimation Methodologies for the Oil and Natural Gas Industry - API, accessed May 2, 2025,

[131] miq.org, accessed May 3, 2025

[132] Comparative life cycle assessment of various ammonia production methods, accessed May 3, 2025

Green Electrolysis (Wind)	< ~0.3 (estimated)	LCA including embodied emissions. Lower end of green spectrum. Estimate based on H_2 intensity + synthesis.	133
Green Electrolysis (Solar PV)	~0.51	LCA including embodied emissions. Higher end of green spectrum due to PV manufacturing emissions. Varies significantly with solar irradiance.	
Green Electrolysis (GH2 Standard)	≤ 0.3	Threshold based on operational emissions (electricity, fugitives, cooling), excluding embodied infrastructure emissions. Average over 12 months.	134

Note: Values are indicative and depend heavily on specific project parameters, LCA methodology, and boundary definitions. Direct comparison requires harmonized methodologies.

Evaluating pathways against the "lowest greenhouse gas intensity" criterion suggests that green ammonia, particularly when produced using low-embodied-emission renewables like hydro or wind, offers the lowest theoretical potential. Blue ammonia's competitiveness hinges critically on achieving very high capture rates *and* near-elimination of upstream methane emissions. In regions with excellent renewable resources, blue ammonia may struggle to meet the "lowest intensity" requirement compared to optimized green pathways, especially considering its long asset lifetime.

4.4 | Resource Efficiency and Use

GS4GG methodologies must ensure activities do not involve technologies or practices constituting an inefficient use of resources crucial for climate mitigation or other policy objectives. This requires assessing the consumption of key inputs like energy and water.

a. **Electricity Consumption:** Green ammonia production via electrolysis is notably energy-intensive.
    i. Reported specific electricity consumption typically ranges from 9.4 to 11 MWh per tonne of NH_3 produced.[135] This includes power for electrolysis, air separation, and the Haber-Bosch synthesis loop.
    ii. Comparing this input energy to the lower heating value (LHV) energy content of ammonia (~5.17 MWh/t NH_3[136]) reveals significant energy conversion losses inherent in the process (overall efficiency often below 50%).

[133] Considering Embodied Greenhouse Emissions of Nuclear and and Renewable Power Plants for Electrolytic Hydrogen and Its Use for Synthetic Ammonia, Methanol, Fischer–Tropsch Fuel Production, accessed May 3, 2025

[134] gh2.org, accessed May 3, 2025

[135] The Future of Ammonia is Green, accessed May 3, 2025

[136] Round-trip Efficiency of Ammonia as a Renewable Energy Transportation Media, accessed May 3, 2025

iii. Electrolyzer efficiency varies by technology, with SOEC offering potentially higher electrical efficiency (lower kWh/kg H_2) due to its high operating temperature utilizing waste heat, compared to AEL or PEM.[137] However, SOEC may have higher degradation rates.

b. **Water Consumption:** Water electrolysis, the foundation of green ammonia, requires substantial quantities of high-purity water.

i. Stoichiometrically, producing 1 tonne of hydrogen requires 9 tonnes of water. Since ammonia (NH_3) is approximately 17.6% hydrogen by mass, producing 1 tonne of NH_3 requires roughly 0.176 tonnes of H_2. This implies a theoretical minimum water input of $0.176\times9\approx1.58$ tonnes of water per tonne of NH_3 for electrolysis alone.

ii. Studies considering process needs (e.g., cooling tower losses, boiler feed) report higher total water consumption figures, ranging from approximately 1.6 tonnes/tonne NH_3 (excluding cooling) to 2.45 tonnes/tonne NH_3 (including cooling losses).[138]

iii. This level of water consumption can pose a significant challenge, particularly as many regions identified with high solar or wind potential (ideal for green ammonia) are also water-stressed areas (e.g., MENA, parts of Australia, Chile).[139] This creates a potential conflict between climate mitigation goals and water resource sustainability (a water-energy-climate nexus). Relying on desalination adds further energy demand and environmental considerations.

iv. In contrast, conventional SMR requires less direct water input for the reaction itself, estimated around 0.66 tonnes water per tonne NH_3[140], although overall water footprint including cooling may differ.

c. **Land Use:** While the ammonia plant itself has a moderate footprint, the large-scale renewable energy installations (solar farms, wind farms) required to power green ammonia production demand significant land areas.[141] This needs consideration in land-use planning and potential impacts on biodiversity or alternative land uses.

d. **Resource Efficiency Assessment:**

i. The high electricity demand for green ammonia raises questions about resource efficiency.

ii. Using ammonia as an energy *carrier* (e.g., producing green ammonia, transporting it, then cracking it back to hydrogen for use in fuel cells)

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[137] Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025

[138] Sustainable Ammonia Production Processes - Frontiers, accessed May 3, 2025,

[139] Just Energy Transitions? Lessons From Oman and Morocco, accessed May 3, 2025

[140] Sustainable Ammonia Production Processes - Frontiers, accessed May 3, 2025,

[141] The role of green hydrogen in a just, Paris-compatible transition – New Climate Institute, accessed May 3, 2025

incurs further significant energy losses. Round-trip efficiencies (renewable electricity input to final energy service output) can be low, potentially ranging from 11% to 31% depending on the pathway and end-use technology. This highlights potential inefficiency if used where direct hydrogen transport or direct electrification is viable.

iii. The high water consumption of electrolysis presents a resource efficiency challenge in water-scarce regions. Prioritizing green ammonia production that exacerbates local water stress could be deemed an inefficient use of a critical resource.

iv. Comparing pathways[142]: Green ammonia avoids fossil fuel feedstock dependency but is intensive in renewable electricity and water. Blue ammonia reduces direct CO_2 but remains dependent on fossil natural gas (a finite resource) and requires additional energy for CCS. Grey ammonia is the most fossil-fuel intensive. From a pure resource perspective (excluding emissions), grey/blue pathways might appear more efficient in terms of primary energy input (GJ/t NH_3) due to the established SMR process, but this ignores the climate externality. Green ammonia's resource efficiency is tied directly to the efficiency of renewable electricity generation and electrolysis.

Table 7: Resource Consumption Comparison for Low-Carbon Ammonia Production (Indicative)

Pathway	Primary Energy Feedstock	Electricity Input (MWh/t NH_3)	Water Input (t H_2O / t NH_3)	Notes	Relevant Sources
Grey SMR (No CCS)	Natural Gas	Lower (process heat from NG)	~0.66 (process) + cooling	Water primarily for steam reforming & cooling.	143
Blue SMR/ATR + CCS	Natural Gas	Moderate (for CCS unit)	Similar to Grey + CCS needs	Additional energy needed for CO_2 capture/compression. Water use similar to grey plus potential CCS needs.	144(Implied)
Green Electrolysis (AEL/PEM)	Water	~9.4 - 11	~1.6 - 2.5	High electricity demand for electrolysis/ASU/HB. High purity water needed for electrolysis; includes cooling.	145

[142] Industrial ammonia production emits more CO2 than any other chemical-making reaction. Chemists want to change that - C&EN, accessed May 2, 2025,

[143] Sustainable Ammonia Production Processes - Frontiers, accessed May 3, 2025,

[144] Green and Blue Ammonia - Fertilizer Industrial Services, accessed May 3, 2025,

[145] The Future of Ammonia is Green, accessed May 3, 2025

Green Electrolysis (SOEC)	Water (Steam)	Potentially Lower (<9.4)	Similar to AEL/PEM	Higher electrical efficiency possible if waste heat available, but higher degradation.	[146]

Note: Values are approximate and vary based on technology specifics, plant scale, and operating conditions. Electricity input for Grey/Blue pathways primarily covers auxiliary equipment unless specified otherwise.

The analysis suggests that while green ammonia offers a path to decarbonization, its high demand for renewable electricity and water necessitates careful consideration under the resource efficiency criterion.

4.5 | Alignment with National Circumstances and Long-Term Strategies

The compatibility of low-carbon ammonia projects with long-term climate goals is intrinsically linked to the specific context of the host country. The methodology requires that activities be consistent with the host country's submitted LT-LEDS and NDC, and that the analysis considers national circumstances, path dependencies, and the availability of alternatives.

a. **Consistency with LT-LEDS/NDCs:** Many countries are developing national hydrogen strategies. However, these strategies are often recent and may not yet be fully reflected or integrated into the official LT-LEDS submitted to the UNFCCC.[147] LT-LEDS provide the formal long-term vision against which activities should be assessed for consistency. A potential misalignment could arise if a project is based on a new hydrogen strategy that deviates significantly from, or is not yet incorporated into, the country's official LT-LEDS. This poses a compliance risk for projects seeking crediting, potentially requiring updates to national LT-LEDS to ensure alignment. The project developers must verify consistency with the *latest submitted* LT-LEDS.

b. **National Circumstances and Alternatives:** The optimal low-carbon ammonia pathway and the associated lock-in risks are highly dependent on national circumstances.

   i. *Resource Endowment:* Countries with abundant, low-cost renewable energy potential (e.g., solar in MENA, wind/solar in Australia, hydro/wind/solar in Chile) are naturally positioned for green ammonia production. Conversely, countries with significant natural gas reserves and established infrastructure, coupled with geological storage potential, might view blue ammonia as a viable transition pathway.[148] However, the long-term compatibility risk remains.

   ii. *Water Availability:* As discussed above, water scarcity is a critical national circumstance. In arid regions pursuing green ammonia, the project's water source (e.g., desalination vs. scarce freshwater) and

[146] Coupling solid oxide electrolysis to ammonia production, accessed May 3, 2025

[147] LT-LEDS Synthesis Report - UNFCCC, accessed May 3, 2025,

[148] Stimulating Clean Hydrogen Demand: The Current Landscape - Belfer Center, accessed May 3, 2025

efficiency become paramount in assessing lock-in risk related to resource stress.

iii. *Existing Infrastructure & Path Dependencies:* The presence of existing natural gas pipelines, SMR facilities, industrial clusters, and a skilled workforce can create path dependencies favouring blue ammonia development, particularly for retrofits or expansions. While potentially offering lower initial costs, this can reinforce reliance on fossil fuels.

iv. *Domestic Policy Priorities:* LT-LEDS or national development plans might prioritize certain sectors for decarbonization or specific technological pathways (e.g., direct electrification vs. hydrogen/ammonia for transport or heating).[149] An ammonia project targeting an application discouraged by national long-term strategy could be considered inconsistent.

c. **Availability and Feasibility of Alternatives:** The assessment must consider whether viable, lower-emission or more resource-efficient alternatives exist within the national context. The feasibility assessment should encompass technical, economic, and social factors relevant to the host country.

The lock-in risk profile is different based on the interplay of resource availability, existing infrastructure, policy direction, and economic factors within each host country. Methodologies under GS4GG need flexibility to accommodate this context-specificity while upholding the core principles of long-term climate compatibility and resource efficiency.

4.6 | Scale and Overall Assessment

The scale of proposed low-carbon ammonia projects is often substantial, frequently targeting capacities of hundreds of thousands or even millions of tonnes per year.[150] According to Requirements for additionality demonstration, Section 6.2, the scale of the activity is a factor to be considered in the lock-in analysis.

Large-scale projects inherently amplify the potential consequences of lock-in. Significant capital investment in multi-decade infrastructure creates considerable inertia, making it economically and logistically difficult to pivot to alternative technologies or pathways should they become preferable later. A large-scale green ammonia plant locks in significant demand for renewable electricity and potentially water resources, influencing the development trajectory of the energy and water systems in the region. The sheer size of these investments means that any misstep in aligning with long-term goals can have major, long-lasting repercussions for national and global decarbonization efforts. Therefore, the larger the scale of the proposed activity, the more critical and rigorous the lock-in risk assessment becomes.

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[149] NDC – LT-LEDS alignment guide - | IDDRI, accessed May 3, 2025

[150] Low-Emission Ammonia Data (LEAD): Plants Executive Summary, accessed May 2, 2025

Overall Assessment:

a. **Green Ammonia:** The primary lock-in risks relate to resource inefficiency (high electricity and water demand) and the potential diversion of renewable resources from more efficient direct uses. The lifecycle GHG intensity, while potentially very low, is sensitive to the renewable source used. Long infrastructure lifetimes necessitate ensuring alignment with evolving energy systems. A summary is presented in Table below.

b. **Blue Ammonia:** The primary lock-in risks are its incompatibility with mid-century net-zero goals due to reliance on fossil fuels and residual emissions (imperfect CCS and upstream methane), and the long lifetime of the associated infrastructure potentially creating stranded assets. Its climate benefit is highly contingent on near-perfect methane management and CCS performance.

c. **Turquoise Ammonia:** Risks are similar to blue regarding fossil feedstock dependency and long asset life. Additional uncertainty exists around the management of the solid carbon byproduct and the energy source for pyrolysis.

Table 8: Green Ammonia Lock-in Risk Assessment Summary against GS4GG Criteria

GS4GG Lock-in Criterion	Green Ammonia Production (Electrolysis + Renewables) Assessment	Potential Lock-in Risk	Mitigation/Compliance with GS Methodology Applicability Conditions [1]
1. Creates dependency on fossil fuels	Primarily powered by renewable electricity. No fossil feedstock.	Indirect reliance if grid-tied to fossil-heavy grids or uses fossil backup/auxiliaries.	Dedicated RE supply, 100% RE-certified grid electricity (with strict matching), <0.1% fossil backup runtime with phase-out plan, zero-emission auxiliaries, water as sole H2 feedstock.
2. Extends lifespan of high-emission infrastructure	New greenfield facilities; replaces fossil-based H2 production.	Long lifespan of ASUs (>20 years) and Haber-Bosch loop (>20 years) commits capital to specific site/process.	Electrolyzer modularity allows for upgrades. Overall facility is new, not extending existing fossil infrastructure. Mandatory decommissioning of existing fossil-based H2 equipment for brownfield.
3. Adopts technologies with no decarbonization pathway	Electrolysis (AEL, PEM, SOEC) is a core zero-emission H2 pathway. Haber-Bosch is mature.	High energy/water intensity could be seen as inefficient resource use if better alternatives emerge.	Continuous improvement in electrolyzer efficiency. Sustainable water sourcing. Prioritize applications where direct electrification isn't feasible. Exclusions of high-risk technologies.
4. Triggers market/regulatory shifts favoring fossil fuels	Drives demand for renewable energy, supporting RE market growth.	Very large RE demand could theoretically divert RE from other sectors (e.g., direct electrification).	Project contributes to overall RE capacity expansion. Policy frameworks should prioritize RE for highest and best use. Strict RE sourcing criteria.

5. Consideration of socio-economic contexts, existing infrastructure, and path dependencies	Project design considers local water availability and existing fossil infrastructure.	Potential for water stress in arid regions; path dependencies from existing fossil infrastructure.	Water use limitation (max 5% drinking water). Mandatory decommissioning of existing fossil-based H2 equipment.
6. Technical or operational lifetime of technologies	Components have multi-decade lifetimes.	Long asset life commits capital and resources for decades.	Electrolyzer modularity allows for upgrades. Methodology ensures alignment with long-term climate goals.
7. Emissions intensity of technologies	Near-zero direct emissions. LCA depends on RE source.	Variability in LCA GHG intensity based on RE source and embodied emissions.	Strict RE sourcing criteria (100% RE, temporal matching). Exclusions of high-emission pathways (grey/blue ammonia).
8. Scale of the activity	Large scale amplifies potential consequences.	Significant capital and resource commitment for decades.	Methodology's stringent applicability conditions ensure large-scale projects are inherently low-carbon and resource-efficient.
9. Availability and feasibility of alternative options	Green ammonia is a viable low-carbon alternative.	Other low-carbon alternatives might be more feasible in certain contexts.	Methodology focuses on green ammonia as a specific pathway, with exclusions for other less aligned or unproven alternatives.
10. Potential exemption for technologies with lifetimes ≤ 10 years	Not applicable to entire facility, but electrolyzer stacks have shorter lifetimes.	Entire facility lifetime exceeds 10 years.	While not a blanket exemption, modularity of electrolyzers allows for upgrades. Methodology's safeguards cover the entire long-lived asset.

5| CONCLUSION AND RECOMMENDATIONS

The analysis indicates that the deployment of low-carbon ammonia production technologies, while crucial for decarbonizing certain sectors, carries potential lock-in risks that must be carefully managed to ensure compatibility with the long-term goals of the Paris Agreement. These risks vary depending on the production pathway (green, blue, turquoise) and the specific national and regional context. Blue ammonia faces significant risks related to its long-term incompatibility with net-zero targets due to continued fossil fuel reliance and residual emissions. Green ammonia, while operationally aligned with zero emissions, faces risks associated with high resource consumption (renewable electricity, water) and potential inefficiencies compared to direct electrification, particularly in resource-constrained regions or for certain end-uses.

A green ammonia production facility may be exempted from a detailed activity-level lock-in risk analysis if it can unequivocally demonstrate full compliance with specific, stringent conditions that inherently mitigate lock-in risks. This is justified because green ammonia, by its fundamental design, aligns with the long-term goal of zero direct emissions. Further to the design of the activity, The methodology should include of necessary safeguards within its applicability requirements to address potential lock-in risks. Thus, compliance with the methodology's applicability requirements will demonstrates conformance with eligibility requirements for Lock-in Risk Analysis.

Conditions for Exemption (Justification for inherent low-risk):

- Dedicated 100% Renewable Energy Supply: The facility must be powered exclusively by dedicated, newly built (additional) renewable energy generation assets (e.g., solar, wind farms) with no connection to a fossil-dominated grid, or demonstrate strict 100% temporal and geographical matching with certified renewable energy credits. This ensures no indirect fossil dependency.
- Zero Fossil Backup Systems: The project must operate without any fossil fuel-based backup systems, or if temporary backup is unavoidable during commissioning or extreme events, its runtime must be strictly less than 0.1% annually, with a clear, verifiable plan for its complete elimination within the first crediting period.
- Zero-Emission Auxiliary Systems: All auxiliary systems (e.g., heating, cooling, compression, hydrogen storage/transport) must utilize zero-emission technologies or be powered by the dedicated renewable energy source.[2] No methane-based compressors or pipelines should be used.
- Sustainable Water Sourcing: For projects in water-stressed regions, a detailed water management plan demonstrating sustainable water sourcing (e.g., desalinated seawater with renewable energy, treated wastewater) and highly efficient water use must be provided. This directly addresses the "inefficient use of resources" criterion.
- Modular and Upgradable Design: The design of the electrolysis unit must explicitly allow for future technology upgrades and replacements to ensure continuous improvement in efficiency and to prevent lock-in to specific electrolyzer generations.[2]
- Alignment with Host Country LT-LEDS: The project must explicitly demonstrate consistency with the host country's latest submitted Long-Term Low Emission Development Strategy (LT-LEDS) and Nationally Determined Contributions (NDCs), particularly regarding renewable energy deployment and hydrogen/ammonia pathways.

It is recommended that the methodology shall require following information to be captured in project design document for transparency and identification of any potential risk that may be associated with a given project activity.

Recommended Checklist for Activity-Level Lock-in Risk Assessment

To determine if a green ammonia project is eligible under this methodology and thus inherently addresses lock-in risk (and may be exempted from a separate activity-level lock-in risk analysis), please confirm compliance with the following applicability conditions. If *all* conditions are met, the project is considered compliant with the methodology's lock-in risk requirements. If *any* condition is not met, the project shall conduct a detail lock assessment as per the principles/criteria established in table 8 above.

Condition	Yes / No
Is hydrogen (H_2) production exclusively via water electrolysis? [1]	
Is nitrogen (N_2) production via air separation?	
Is ammonia synthesis via the Haber-Bosch process?	
Is the electrical energy consumed for all significant process stages demonstrated to originate solely from Renewable Energy sources as defined in this methodology?	
Does the annual consumption of grid electricity by the project activity (including all subprocesses for ammonia production) not exceed 10% of the total annual electricity consumption of the project activity?	
If dedicated off-site renewable energy facilities supply the project, do they meet the Origin (COD within 36 months of PIS), Deliverability (same electricity grid region), and Temporal Matching (hourly basis) criteria?	
Is the sole feedstock for hydrogen production within the project boundary water?	
Does the project use no more than 5% of its total water consumption from locally available drinking water or 5% of locally available drinking water supply, whichever is lesser?	
Does the project activity comply with all applicable national and local laws, regulations, and environmental standards?	
If a greenfield electrolyzer is installed within an existing ammonia production facility that previously used fossil-based hydrogen production, is the existing fossil-based hydrogen production equipment decommissioned, destroyed, or verifiably rendered permanently inoperable?	
Does the project activity avoid ammonia production using hydrogen derived from fossil fuels (grey/blue), biomass/waste, or alternative/novel synthesis technologies not explicitly included in this methodology?	

SECTION 3:

Best Available Technology Analysis for Ammonia Production

1| INTRODUCTION

Ammonia (NH_3) occupies a critical position in the global economy, primarily as the foundational chemical for nitrogen-based fertilizers, which are indispensable for modern agriculture and global food security.[151] Approximately 70-85% of the global ammonia output, estimated at around 180-185 million tonnes (Mt) annually in recent years[152], is dedicated to fertilizer production, supporting food cultivation for nearly half the world's population.[153] Beyond agriculture, ammonia serves vital industrial roles in refrigeration, explosives, plastics, and synthetic fibres. Furthermore, ammonia is increasingly recognized for its potential as a low-carbon energy carrier and fuel, particularly for maritime transport and power generation, offering advantages in storage and transport compared to pure hydrogen. This dual role, supporting existing essential industries while potentially enabling future energy systems, underscores the importance of ammonia but also highlights a significant challenge: its substantial carbon footprint.

Current ammonia production methods are highly energy-intensive and overwhelmingly reliant on fossil fuels. Globally, the sector accounts for approximately 1-2% of total final energy consumption and generates around 1.3% of global energy system CO_2 emissions, equating to roughly 450-500 Mt CO_2 annually. [154] The primary source of these emissions is the production of hydrogen (H_2), the key feedstock for the Haber-Bosch ammonia synthesis process, which predominantly uses steam methane reforming (SMR) of natural gas or, particularly in China, coal gasification.[155] The resulting emission intensity averages around 2.4 tCO_2 per tonne of ammonia globally, significantly higher for coal-based routes, making ammonia one of the most emissions-intensive industrial commodities.[156]

Addressing these emissions is critical for achieving the goals of the Paris Agreement and transitioning towards a net-zero future.[157] Establishing clear performance benchmarks based on Best Available Technology (BAT) is a crucial step in this process. BAT benchmarks provide a reference point for current performance, guide

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[151] (PDF) Ammonia Production Plants—A Review - ResearchGate, accessed May 3, 2025,

[152] Ammonia: zero-carbon fertiliser, fuel and energy store - Royal Society, accessed May 3, 2025

[153] H2IQ Hour: Ammonia - From Fertilizer to Energy Carrier, accessed May 3, 2025

[154] H2IQ Hour: Ammonia - From Fertilizer to Energy Carrier, accessed May 3, 2025

[155] Powering the "Green Revolution" with Ammonia? - RTI International, accessed May 3, 2025

[156] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed May 3, 2025

[157] Decarbonizing Ammonia and Nitrogen Fertilizers with Clean Hydrogen - Open Knowledge Repository - World Bank, accessed May 3, 2025

investment towards cleaner technologies, and form the basis for effective climate policy mechanisms, including emissions trading systems and carbon crediting under frameworks of the Paris Agreement.

This section of the report aims to update and enhance understanding of BAT for ammonia production by conducting a regional and country-specific analysis. Its primary purpose is to compile a comprehensive report on BAT determination for ammonia production, strictly adhering to the five-step process outlined GS4GG – Green Ammonia Production methodology. The analysis covers global, regional, and specific country contexts for major ammonia producers, concluding with recommendations supported by evidence from peer-reviewed literature and the research material.

Based on this analysis, the report recommends benchmark emission factors (expressed in tonnes of CO_2 equivalent per tonne of ammonia, tCO_2e/tNH_3) reflecting BAT performance in different contexts.

2| BEST AVAILABLE TECHNOLOGY (BAT) DETERMINATION FRAMEWORK

The concept of Best Available Technology (BAT) is central to regulating and reducing industrial emissions globally. It represents the most effective and advanced stage in the development of activities and their methods of operation, indicating the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole.

2.1 | Objectives and Scope of BAT analysis

The primary objective of this BAT analysis is to identify the most economically viable and environmentally sound technology for ammonia production that aligns with deep decarbonization goals, specifically those compatible with the long-term temperature goals of the Paris Agreement (limiting global warming to well below 2°C, pursuing 1.5°C).1 This objective extends beyond mere emissions reduction to ensure the long-term climate compatibility of investments.

The scope of this BAT analysis is comprehensive, encompassing the entire ammonia production process. The focus is exclusively on ammonia production via hydrogen and nitrogen synthesis, including all major current and emerging technologies for hydrogen production (e.g., Steam Methane Reforming (SMR), Autothermal Reforming (ATR), electrolysis) and nitrogen separation (e.g., cryogenic air separation). Novel or alternative methods, such as direct electrochemical synthesis or methane pyrolysis, are acknowledged, but their current commercial viability and Technology Readiness Levels (TRL) are assessed to determine their applicability within the scope. Furthermore, the assessment incorporates compliance with national environmental regulations, including emissions limits and energy efficiency standards, and alignment with international agreements such as the Paris Agreement, national net-zero targets, and Nationally Determined Contributions (NDCs). The economic context is also explicitly considered, with the analysis accounting for carbon pricing mechanisms (whether zero or a domestic carbon price/tax) as a critical factor influencing economic viability and technology selection.

2.2 | Evaluation Criteria for BAT Selection in Ammonia Production

Drawing specifically from the UNFCCC draft standard for setting baselines (A6.4-MEP004-A01), the selection of BAT for ammonia production should adhere to specific criteria.[158] The BAT approach is applicable when:

a. Emissions or removals per unit of output are primarily determined by the specific technology or practice employed.
b. Sufficient and reliable data are available to identify and assess the BAT.

This approach is particularly suitable when an activity involves a single, well-defined technology (like installing a specific type of electrolyzer or reformer) or when alternative technologies provide reasonably homogeneous outputs (e.g., producing ammonia of a standard grade). Crucially, if a host Party has already mandated a specific technology as BAT, that definition must be applied. The identification of the specific BAT involves a multi-step assessment involving the following criteria:

a. **Economic Viability:** This criterion assesses the financial attractiveness and cost-effectiveness of each technology. It involves evaluating Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), calculating the Levelized Cost of Ammonia (LCOA) production, analyzing sensitivity to carbon pricing, and assessing payback period and Return on Investment (ROI). The economic viability of low-carbon pathways, such as green ammonia, is often not self-sustaining without significant policy intervention, as its cost premium can range from 10% higher to potentially more than double, or even six times higher than grey ammonia. Policy interventions, such as the US Inflation Reduction Act (IRA) tax credits and EU Renewable Fuels of Non-Biological Origin (RFNBO) quotas, substantially improve the economics of low-carbon ammonia. This indicates that BAT selection is heavily influenced by the prevailing policy environment, rather than purely technological cost curves, especially in the near term.
b. **Environmental Performance:** This criterion focuses on the overall environmental footprint of the technology. It includes quantifying Greenhouse Gas (GHG) emissions intensity (tCO_2e per tonne NH_3), assessing energy efficiency (GJ per tonne NH_3), evaluating resource use (such as water consumption for electrolysis and land use for renewables), and considering waste generation and byproduct management. The UNFCCC framework emphasizes using technologies with the "lowest feasible greenhouse gas intensity for long-lifetime investments". Ammonia plants, whether conventional, blue, or green, have core components with operational lifetimes potentially extending beyond 20 years. This creates a tension, as investments in blue ammonia, even with high carbon capture rates, still rely on fossil fuel-based infrastructure and carry residual emissions and upstream methane leakage risks, potentially locking in fossil fuel dependence for decades and misaligning

158 UNFCCC.int, accessed May 3, 2025

with 2050 net-zero goals. This implies that "lowest feasible" is a dynamic concept that must be interpreted against the Paris Agreement's long-term temperature goals. A technology feasible today might become a "lock-in" risk if its emissions profile is incompatible with future, more stringent targets. Therefore, BAT selection must consider not just current feasibility but also future compatibility with net-zero, potentially favoring technologies that can achieve near-zero emissions over their entire lifespan, even if they are currently more expensive, often pointing towards green ammonia as the ultimate long-term solution.

c. **Regulatory Compliance:** This criterion assesses adherence to legal and policy frameworks. It involves verifying compliance with national environmental regulations, including emissions limits, energy efficiency standards, and other relevant permits. Additionally, it checks compatibility with international agreements such as the Paris Agreement goals, Nationally Determined Contributions (NDCs), and Long-Term Low Emission Development Strategies (LT-LEDS).

d. **Technical Feasibility:** This criterion evaluates the practical readiness and operational aspects of the technology. It assesses the scalability and maturity of the technology, determining if it is proven at a commercial scale and its Technology Readiness Level (TRL). It also considers the availability of necessary infrastructure, such as natural gas pipelines, renewable energy sources, CO_2 storage sites, and sufficient water resources. Operational reliability and maintenance requirements, including challenges related to intermittency for green ammonia, are also evaluated.

e. **Social and Strategic Factors:** This criterion considers broader societal and national implications. It includes assessing the contribution to job creation and local economic impact, the effect on energy security and reliance on imports, and public acceptance of the technology. Furthermore, it evaluates alignment with national energy transition strategies and broader plans for decarbonization and energy system transformation. The emphasis on "Energy Security and Independence" as a driver for green ammonia indicates a significant shift in strategic thinking, as energy security can be achieved through domestic renewable energy potential rather than fossil fuel reserves. This dual benefit—addressing climate change while bolstering national energy security—can accelerate its deployment beyond purely economic considerations, transforming the concept of energy security from fossil fuel dependence to renewable resource independence.

BAT can be defined in three ways: accepting host party recommendations approved by the Supervisory Body, defining BAT within the methodology using robust data, or providing a procedure for activity developers to identify BAT themselves following the steps above.[80] The geographical scope for BAT determination must also be clearly defined and justified.

The application of BAT criteria necessitates a careful evaluation of these factors within specific regional contexts, acknowledging that the "best" technology pathway may differ based on local resources, infrastructure, policies, and economic conditions.

Furthermore, the identification of BAT requires robust and recent data, which can be a challenge, particularly for comparing the performance and costs of rapidly evolving low-carbon technologies across different geographies. Where data is uncertain or incomplete, a conservative approach is warranted in setting benchmarks.

2.3 | Candidate Technologies for Ammonia Production

The production of ammonia involves several distinct technological pathways, ranging from mature conventional methods to emerging low-carbon alternatives. The BAT criteria apply differently across the spectrum of ammonia production technologies:

a. **Conventional Ammonia Production Technologies (SMR, ATR, Coal Gasification):** These technologies are mature and widely deployed.[159] BAT determination focuses on identifying the most energy-efficient and lowest-emitting configurations currently operating or available, considering factors like heat integration, catalyst performance, and process optimisation.[160] Economic feasibility is generally well-established, but varies with feedstock price (natural gas vs. coal).[161] Environmental soundness relates to meeting local air and water emission standards beyond CO_2. Availability is high globally, though specific advanced designs may be less widespread.

    i. **Steam Methane Reforming (SMR):** This is the most prevalent method globally, accounting for over 70% of ammonia production. It uses natural gas (methane) as both a feedstock and an energy source. The process involves methane reacting with steam to produce hydrogen (H_2) and carbon monoxide (CO), followed by a water-gas shift reaction to produce more H_2 and carbon dioxide (CO2), which is then removed. Finally, purified hydrogen and nitrogen (obtained from air) are fed into the Haber-Bosch synthesis loop to form ammonia. SMR is technologically mature and optimized, achieving significant economies of scale, with typical modern plants ranging from 0.7 to 1.2 Mtpa, and the largest single-train plants reaching up to 3.5 Mtpa. However, it is highly energy-intensive and carbon-intensive, typically emitting 1.8-2.5 tonnes of CO_2 per tonne of ammonia, with a global average of about 2.1 tCO_2/tNH_3.

    ii. **Autothermal Reforming (ATR):** This technology is an alternative hydrogen production method that combines partial oxidation with steam reforming. It is often considered more energy-efficient than SMR, especially for new, large-scale plants. While its emissions profile is similar to SMR, ATR is generally more suitable for carbon capture due to the higher concentration of CO_2 in its off-gas.

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[159] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[160] Ammonia technology portfolio: optimize for energy efficiency and carbon efficiency, accessed May 3, 2025

[161] Low-Carbon Ammonia Roadmap (2023-03) – IEA GHG, accessed May 3, 2025

iii. **Coal Gasification:** This method is particularly prevalent in China, where it accounts for approximately 75-85% of the country's ammonia production. It involves gasifying coal to produce synthesis gas (syngas), from which hydrogen is derived. Although a mature technology, coal gasification is generally less energy-efficient and significantly more polluting than natural gas-based SMR, with the highest emission intensity, averaging around 4.6 tCO_2/tNH_3.

b. **Low-Carbon Ammonia Production Technologies (Blue and Green Ammonia):**

i. **Blue Ammonia (SMR/ATR with Carbon Capture and Storage - CCS):** This pathway starts with conventional SMR or ATR using natural gas to produce hydrogen, but it integrates Carbon Capture, Utilization, and Storage (CCUS) technology to capture a significant portion (typically targeting >90%) of the CO_2 generated [162] The captured CO2 is then transported and permanently stored underground or used in other industrial processes. Blue ammonia utilizes mature SMR/ATR and Haber-Bosch technologies, with CCS being a mature but less widely deployed industrial technology (TRL 8-9). While it significantly reduces direct emissions (potentially to 0.1-0.3 $tCO2e/tNH_3$), its overall climate benefit depends heavily on the actual CO_2 capture rate, the energy penalty of capture, the permanence of CO_2 storage, and, crucially, upstream methane emissions from the natural gas supply chain. Methane leakage can contribute approximately 0.4 kg CO_2e/kg NH_3 to the baseline SMR pathway, potentially diminishing the climate benefits. Economically, blue ammonia is currently considered less expensive than green ammonia, with an estimated cost premium of about 40% over conventional (grey) ammonia, and its viability relies heavily on access to affordable natural gas and CO_2 transport and storage infrastructure. Availability is limited by the need for suitable geological storage sites and CO_2 transport infrastructure.[163]

ii. **Green Ammonia (Water Electrolysis using Renewable Energy):** This pathway uses "Green Hydrogen," produced through water electrolysis powered exclusively by renewable energy sources like solar, wind, geothermal, or hydropower.[164] Nitrogen is obtained from air using an Air Separation Unit (ASU), which must also be powered by renewable energy to maintain "green" credentials. This green hydrogen and nitrogen mixture is then fed into the Haber-Bosch synthesis loop. While the Haber-Bosch process is mature, its integration with large-scale, potentially variable hydrogen supply from electrolysis is a newer

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[162] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[163] Ammonia industry net-zero tracker - The World Economic Forum, accessed May 3, 2025

[164] Powering the “Green Revolution” with Ammonia? - RTI International, accessed May 3, 2025

challenge (TRL 7-8). Current operational green ammonia capacity is very limited (<0.1 Mtpa in late 2024), but many GW-scale projects are announced globally. Direct CO_2 emissions from the production process are virtually zero. However, cradle-to-gate Life Cycle Assessment (LCA) emissions, which include the manufacturing and deployment of renewable energy infrastructure, can range from 0.1 to 0.7 tCO_2e/tNH_3, depending on the specific renewable electricity source and system boundaries. The GH2 Green Ammonia Protocol sets a threshold of $\leq$ 0.3 kg CO_2e/kg NH_3 for green ammonia. Economically, green ammonia production costs are currently significantly higher than conventional grey or blue ammonia, often cited as having a cost premium of 120% or more. The main cost drivers are the price of renewable electricity and the capital expenditure (CAPEX) for electrolysers, though costs are rapidly falling. Green ammonia production is also highly energy-intensive, requiring approximately 9.4 to 11 MWh of electricity per tonne of ammonia, mostly for electrolysis. Additionally, it requires substantial quantities of high-purity water (1.6 to 2.5 tonnes of water per tonne of ammonia), which can be a challenge in water-stressed regions with high renewable potential. Environmental soundness is high regarding direct emissions, but LCA impacts depend on the renewable source and manufacturing footprint.[165]

Global operational capacity derived purely from renewable electrolysis remains extremely limited, estimated at a mere 0.068 Mtpa (67.6 ktpa) as of late 2024. These operational facilities are typically small-scale, often serving as pilot or demonstration projects, or representing initial decarbonization steps at existing ammonia production sites. Examples include plants in Spain (Puertollano, 17 ktpa), Norway (Porsgrunn, 20.5-25 ktpa), and the USA (Donaldsonville, 20 ktpa).

Table 9 highlights selected operational commercial-scale green ammonia plants. (as of late 2024)

Location (Country, Site)	Operator(s)	Capacity (ktpa NH3)	Electrolyzer Type/Size (MW)	Energy Source	Status/Start Year
Porsgrunn, Norway	Yara International	20.5 - 25	PEM / 24 MW	Hydro / Grid	Operational 2024
Donaldsonville, LA, USA	CF Industries	~20	Alkaline / 20 MW	Grid / PPA	Operational 2024
China (Unspecified)	Unspecified	~20	Alkaline / Size N/A	Renewables	Operational 2024
Puertollano, Spain	Iberdrola / Fertiberia	~17	PEM / 20 MW	Solar / Battery	Operational 2022

[165] Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products - OSTI, accessed May 3, 2025,

USA (Unspecified)	Unspecified	~7	Alkaline / Size N/A	Water Electrolysis	Operational 2024
Bikaner, India	ACME Group (Pilot)	~1.5	Alkaline / 4 MW	Solar	Operational 2021
Canada (Unspecified)	Unspecified	~0.1	Alkaline / Size N/A	Water Electrolysis	Operational 2024

Note: Based on available data. Capacities and start years are approximate. Focuses on plants >0.1 ktpa with confirmed operational status post-2020.

c. **Emerging Pathways (e.g., Turquoise Ammonia, Novel Methods):** Research is ongoing into fundamentally different ammonia synthesis methods.

i. **Turquoise ammonia** involves methane pyrolysis, where natural gas is decomposed into hydrogen gas and solid carbon using high temperatures. This route avoids direct CO_2 emissions from hydrogen production, but its viability depends on the energy source for pyrolysis and the effective management (e.g., sequestration or utilization) of the solid carbon co-product. Its technological readiness level is currently lower than green or blue pathways.

ii. **Novel/Alternative Methods**, such as direct electrochemical nitrogen reduction (NRR), plasma-assisted synthesis, and biological nitrogen fixation pathways, are at much earlier stages of development (TRL 1-4) and are not yet commercially viable for large-scale production.

d. **Ancillary Technologies**

These components are essential for the overall functionality of ammonia production plants across various pathways.

i. **Nitrogen Production (Air Separation Units - ASU, Pressure Swing Adsorption - PSA):** Nitrogen (N_2) is a key feedstock for ammonia synthesis. Cryogenic Air Separation Units (ASUs) are the standard technology for large-scale nitrogen production, known for their high efficiency but also energy intensity. For green ammonia, ASUs must be powered by renewable electricity to maintain the product's environmental credentials. Pressure Swing Adsorption (PSA) is another method suitable for smaller-scale operations.

ii. **Ammonia Synthesis (Haber-Bosch Process):** This is the core chemical synthesis loop where purified hydrogen and nitrogen react under high pressure and temperature over an iron-based catalyst to form ammonia. This process is technologically mature and highly reliable, forming the backend of all major ammonia production pathways, whether conventional, blue, or green.

3| COMPARATIVE ANALYSIS OF AMMONIA PRODUCTION TECHNOLOGIES

A detailed comparison of candidate technologies is essential for identifying the Best Available Technology (BAT) for ammonia production. This analysis evaluates each technology against the established criteria, considering global performance, regional specificities, and the influence of policy and economic factors.

3.1 | Global Ammonia Production: Technology Mix and Emission Performance

Understanding the current performance landscape of the global ammonia industry is fundamental to establishing meaningful BAT benchmarks. This involves analyzing the prevalent production technologies, their associated emission intensities, and the potential offered by best practices and emerging low-carbon pathways.

3.2 | Overview of Major Producing Regions/Countries and Technology Mix

Global ammonia production is geographically concentrated, with a few key players dominating the market. China stands as the largest producer, responsible for approximately 30% of the global output in recent years.[166] Other major producers include Russia, India, and the United States, each contributing around 7-11% of global production, followed by significant contributions from Indonesia, Trinidad and Tobago, Saudi Arabia, Canada, and Qatar. The European Union collectively also represents a major production bloc.[167] The technology mix varies significantly by region, largely dictated by feedstock availability and cost. Globally, natural gas is the dominant feedstock, utilized in roughly 72% of ammonia production, primarily through Steam Methane Reforming (SMR) or, increasingly for new large-scale plants, Autothermal Reforming (ATR).[168] Coal gasification accounts for a substantial share, around 22-26%, driven almost entirely by its prevalence in China. Oil products (like heavy fuel oil or naphtha) and electrolysis currently make up the small remainder (around 1-4% and <1%, respectively). This global picture masks significant regional disparities. China's industry is heavily reliant on coal (~75-85% of its production). In contrast, regions like the USA, Russia, and the Middle East leverage abundant and often low-cost natural gas, making SMR the dominant technology. India presents a more mixed picture, historically using naphtha and fuel oil alongside natural gas, although natural gas is now the primary feedstock (~80%).[169] The EU also relies predominantly on natural gas.[170]

[166] Ammonia Production Processes from Energy and Emissions Perspectives: A Technical Brief | C-THRU, accessed May 3, 2025

[167] Low-Carbon Ammonia Roadmap (2023-03) - IEAGHG, accessed May 3, 2025

[168] Ammonia Production Processes from Energy and Emissions Perspectives: A Technical Brief | C-THRU, accessed May 3, 2025

[169] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[170] In the Future Energy System - Hydrogen Europe, accessed May 3, 2025

3.3 | Current Emission Intensities

The variation in feedstocks and plant efficiencies leads to a wide range of emission intensities globally. The global average direct CO_2 emission intensity from ammonia production is estimated to be around 2.4 tCO_2/tNH_3.[171] However, this average masks significant differences. Natural gas-based SMR plants typically average around 2.1 tCO_2/tNH_3, while coal gasification routes average much higher, around 4.6 tCO_2/tNH_3.[172] Life cycle assessments (LCA), considering cradle-to-gate emissions (including upstream feedstock extraction and processing), generally report slightly higher figures, around 2.6 tCO_{2e}/tNH_3 for conventional SMR[173] and potentially 5.1-7.8 tCO_2e/tNH_3 for coal gasification.[174]

A significant gap exists between this average performance and what is achievable with Best Available Technology (BAT).

- **Natural Gas SMR BAT:** Modern, highly efficient SMR plants achieve direct emissions of approximately **1.6 tCO_2/tNH_3**.[175] This corresponds to a net energy consumption of around **28 GJ/tNH_3** (LHV basis).[176]
- **Coal Gasification BAT:** The BAT for coal gasification routes results in significantly higher direct emissions, around **3.8 tCO2/tNH_3**[177], with energy consumption around **36-42 GJ/tNH_3**.[178]
- **ATR + CCS BAT:** While still less common for ammonia than SMR, ATR technology, particularly when integrated with CCS, offers potential for very low direct emissions, potentially below **0.1-0.2 tCO_2/tNH_3**, with energy consumption comparable to or slightly better than SMR BAT (~28-29 GJ/tNH_3).[179]

The International Fertilizer Association (IFA) benchmarking studies confirm this performance gap. The 2008 survey found an average net energy efficiency of 36.6

[171] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed May 3, 2025

[172] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[173] Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products - OSTI, accessed May 3, 2025

[174] Comparative techno-economic and life cycle greenhouse gas assessment of ammonia production from thermal decomposition of methane - Hull Repository, accessed April 11, 2025

[175] H2IQ Hour: Ammonia - From Fertilizer to Energy Carrier, accessed May 3, 2025

[176] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[177] H2IQ Hour: Ammonia - From Fertilizer to Energy Carrier, accessed May 3, 2025

[178] Ammonia technology portfolio: optimize for energy efficiency and carbon efficiency, accessed May 3, 2025

[179] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

GJ/tNH_3 across 93 plants, while the top quartile performed between 28-33 GJ/tNH_3.[180] By 2014, the global average had improved slightly to 36 GJ/tNH_3. IFA estimates that adopting BAT globally could reduce average energy use by 20-25% and GHG emissions by approximately 30%.[181] This highlights that substantial decarbonization can be achieved simply by upgrading existing facilities and shifting away from coal towards best-in-class natural gas reforming, even before widespread deployment of CCS or electrolysis.

3.4 | Performance of Low-Carbon Pathways

Two primary pathways are emerging for near-zero emission ammonia production: blue ammonia (conventional routes with CCS) and green ammonia (electrolysis with renewable power).

a. **Blue Ammonia (SMR/ATR + CCS):** This pathway aims to capture CO_2 emissions generated during hydrogen production.
   i. *Emissions Performance:* Technology providers claim high capture rates (up to 99%+) for the concentrated process CO_2 stream, particularly with ATR designs.[182] This can lead to very low direct process emissions, potentially 0.1-0.3 tCO_2e/tNH_3. However, conventional SMR also produces CO_2 in flue gas from heating the reformer, which is more dilute and costly to capture; capturing only process CO_2 might not meet stringent low-carbon thresholds (e.g., EU definitions).[183] ATR avoids external firing, making capture easier. The overall life cycle footprint is highly sensitive to the actual CO_2 capture rate achieved, the energy penalty of capture, the permanence of CO_2 storage, and crucially, upstream methane emissions from natural gas extraction and transport. High methane leakage rates can significantly erode or even negate the climate benefits of blue ammonia/hydrogen.[184]
   ii. *Economics & Deployment:* Blue ammonia is generally considered less expensive than green ammonia currently, with an estimated cost premium of around 40% over conventional (grey) ammonia. Its viability depends heavily on access to affordable natural gas and CO_2 transport and storage infrastructure.[185] Current global blue ammonia production is

[180] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[181] Ammonia technology portfolio: optimize for energy efficiency and carbon efficiency, accessed May 3, 2025

[182] Global Syngas Technologies Council - Blue before Green?, accessed May 3, 2025

[183] In the Future Energy System - Hydrogen Europe, accessed May 3, 2025

[184] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[185] Low-Carbon Ammonia Roadmap (2023-03) - IEAGHG, accessed May 3, 2025

minimal (~1 Mt/year), but significant capacity (~40 MT) is planned, particularly in North America leveraging CCS incentives.[186]

b. **Green Ammonia (Electrolysis + Haber-Bosch):** This pathway eliminates fossil fuels from the hydrogen production step.

   i. *Emissions Performance:* Direct emissions from the production process are virtually zero. However, the cradle-to-gate LCA emissions are highly dependent on the source of electricity used for electrolysis and the Haber-Bosch synthesis loop. Using dedicated wind or solar power results in very low LCA emissions, with reported values typically ranging from **0.1 to 0.7 tCO_2e/tNH_3.**[187] Using grid electricity can lead to much higher emissions if the grid mix has a significant fossil fuel share; in some cases, emissions could exceed those of conventional SMR. Other factors influencing LCA include electrolyzer efficiency (typically 50-80%[188]), emissions embodied in renewable energy infrastructure and electrolyzers, and water sourcing.

   ii. *Economics & Deployment[189]:* Green ammonia is currently significantly more expensive than grey or blue ammonia, often cited as having a cost premium of 120% or more. The primary cost driver is the price of renewable electricity and the capital cost of electrolyzers. Costs are falling, and green ammonia may be competitive in regions with exceptionally low renewable electricity prices. Despite the cost challenge, there is significant global interest, with a large pipeline of announced electrolysis projects (~180 MT H_2 capacity, though not all dedicated to ammonia). Actual operational green ammonia capacity remains very small (<1% of global production).

Table 10: Global Ammonia Production Technologies & Emission Performance

Technology Pathway	Feedstock	Avg. Energy Intensity (GJ/t NH_3)	BAT Energy Intensity (GJ/t NH_3)	Avg. Direct Emissions (tCO_2/t NH_3)	BAT Direct Emissions (tCO_2/t NH_3)	Typical LCA Emissions (tCO_2e/tNH_3, Cradle-to-Gate)	Technology Readiness Level (TRL)	Key References
SMR	Natural Gas	~37-41	~28	~2.1	~1.6	~2.6	9 (Mature)	[190]

[186] Ammonia Production Processes from Energy and Emissions Perspectives: A Technical Brief | C-THRU, accessed May 3, 2025

[187] Environmental Life Cycle Assessment of Ammonia-Based Electricity - MDPI, accessed May 3, 2025

[188] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[189] Ammonia industry net-zero tracker - The World Economic Forum, accessed May 3, 2025

[190] Ammonia technology portfolio: optimize for energy efficiency and carbon efficiency, accessed May 3, 2025

Coal Gasification	Coal	~49 (China Avg)	~36-42	~4.6	~3.8	~5.1-7.8	9 (Mature)	191
SMR + CCS	Natural Gas	~32 (process capture)	~30-32 (full capture likely higher)	Variable (depends on capture rate)	<0.2 (with high capture)	~0.2 - 1.0+ (highly sensitive to capture rate & CH_4 leakage)	8-9 (Commercial)	192
ATR + CCS	Natural Gas	~28-29	~28	Variable (depends on capture rate)	<0.1 - 0.2 (high capture easier)	~0.1 - 0.8+ (sensitive to capture rate & CH_4 leakage)	8-9 (Commercial)	193
Electrolysis (Renewable) + HB	Water, Air, Renewable Electricity	Variable (~36-50+ depending on source & efficiency) [55]	N/A (Efficiency focus)	~0	~0	~0.1 - 0.7 (dependent on RE source & system boundary)	7-8 (Demonstration to Commercial)	194

Notes: Emission intensities are indicative and vary based on specific plant design, efficiency, feedstock quality, operational practices, and LCA methodology/boundaries. Energy intensity is LHV basis. LCA emissions are cradle-to-gate.

The significant difference between average global performance and BAT levels, particularly for natural gas reforming, underscores a substantial opportunity for near-term emission reductions through the diffusion of existing efficient technologies and practices. Furthermore, the variability and context-dependency of low-carbon pathway performance, especially concerning upstream emissions for blue ammonia and electricity sources for green ammonia, necessitate careful, regionally specific assessment when defining future BAT benchmarks.

3.5 | Regional and Country-Specific BAT Analysis and Benchmarking

Applying the BAT principles and criteria outlined above requires a nuanced analysis tailored to the specific circumstances of major ammonia-producing regions and countries. Factors such as dominant feedstock, age and efficiency of the existing industrial base, national climate policies and targets (NDCs), energy costs, infrastructure availability (e.g., for CCS or renewables), and economic conditions significantly influence what constitutes the Best Available Technology in a given location.

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[191] Ammonia Production Processes from Energy and Emissions Perspectives: A Technical Brief | C-THRU, accessed May 3, 2025

[192] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[193] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - Sustainable Energy & Fuels (RSC Publishing) DOI:10.1039/D3SE01421E, accessed May 3, 2025

[194] Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products - OSTI, accessed May 3, 2025,

The following table provides an overview of ammonia production in key regions and countries, including estimated 2023 production, primary feedstocks, dominant technology, estimated average emission intensity, and key policy drivers:

Table 11: Regional/Country Ammonia Production Overview

Region/ Country	Est. 2023 Production (Mt NH_3)	Primary Feedstock(s) (%)	Dominant Technology	Est. Avg. Emission Intensity ($tCO2e/tNH_3$, LCA)	Key Policy Drivers	Reference
China	~56 (2022) (~43 in 2023)	Coal (~75-85%), NG (~24%)	Coal Gasification, SMR	High (~4.4-4.9 GJ/t, ~4.4-4.6 tCO_2/t direct avg)	Dual Carbon Goals (Peak <2030, Neutrality 2060), NDRC Action Plan, Green H_2/Ammonia Promotion, ETS	195
India	~14 (2023)	NG (~80%), Naphtha (~9%), Oil (~10%)	SMR, Naphtha Reforming	Moderate (~37.7 GJ/t avg)(~2.3 tCO_2/t avg direct)	Net Zero 2070, National Hydrogen Mission (NHM), Energy Security/Import Reduction, Fertilizer Efficiency	196
USA	~14 (2023)	NG (~97-100%)	SMR	Low-Moderate (~35-38 GJ/t avg) (~2.1 tCO_2/t avg direct)	Inflation Reduction Act (IRA - 45V, 45Q), Methane Regulations, Hydrogen Hubs	
EU	~17.7 capacity (Production lower due to curtailments)	NG (dominant)	SMR	Low (~32.5-36 GJ/t avg) (~2.0 tCO_2/t avg direct)	Fit for 55, EU ETS, CBAM, RED II, BREF/BAT Conclusions	197
Russia	~14 (2023)	NG (~100%)	SMR	Moderate-High (~40 GJ/t avg) (~2.2 tCO_2/t avg direct)	Low-Carbon Strategy, Hydrogen Concept, Export Focus	198
Middle East (KSA, QAT, UAE)	~12.7 (2010) (Likely higher now)	NG (~100%)	SMR	Low (~36 GJ/t avg) (~2.0 tCO_2/t avg direct)	Net Zero Targets (Varying), Economic Diversification, H_2/Ammonia Hub Ambitions (Blue & Green)	199

Note: Production figures and intensities are indicative and subject to annual variations and data source differences. LCA intensity estimates are generally higher than direct emission intensity.

[195] Ammonia Production Processes from Energy and Emissions Perspectives: A Technical Brief | C-THRU, accessed May 3, 2025

[196] Decarbonizing Ammonia and Nitrogen Fertilizers with Clean Hydrogen - Open Knowledge Repository - World Bank, accessed May 3, 2025

[197] In the Future Energy System - Hydrogen Europe, accessed May 3, 2025

[198] March 2025 Project Features introduction - Ammonia Energy Association, accessed May 3, 2025

[199] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed May 3, 2025

3.5.1 | China

China's position as the world's largest ammonia producer and consumer, coupled with its heavy reliance on coal gasification (~75-85%), makes its decarbonization path uniquely challenging but globally significant. The high average energy intensity (~49 GJ/t) and direct CO_2 emissions (~4.4 tCO_2/t) of its fleet reflect this coal dominance, although some more efficient natural gas-based SMR plants also operate. Significant efforts have been made to close inefficient, smaller coal-based plants[200], but the overall emissions remain high, contributing disproportionately (~45%) to global ammonia sector emissions. Policy is a major driver of change. China's "dual carbon" goals (peak CO_2 before 2030, carbon neutrality by 2060) provide the overarching framework. Specific actions include the National Development and Reform Commission's (NDRC) plan to reduce ammonia industry CO_2 emissions by 13 Mt by 2025 through efficiency upgrades and retrofits.[201] Benchmarking energy efficiency is a key compliance consideration for industries including ammonia synthesis.[202] Furthermore, China is actively promoting green hydrogen and ammonia, leveraging its massive renewable energy deployment (especially wind and solar) and world-leading electrolyzer manufacturing capacity.[63] Pilot projects co-firing ammonia in coal power plants are also underway. While a national emissions trading scheme exists, its expansion to the chemical sector, including ammonia, is anticipated but not yet fully implemented.[93]

a. BAT Analysis for China:
   i. **Conventional BAT:** Given the existing infrastructure and policy focus on efficiency, the BAT for conventional production should reflect modern, efficient coal gasification (~3.8 tCO_2/t direct) [62] or natural gas SMR (~1.6 tCO_2/t direct) [62], rather than the current fleet average.
   ii. **Low-Carbon BAT:** Blue ammonia via coal gasification with CCS faces significant hurdles due to the high cost and limited deployment of CCS in China.[64] The clear policy direction and rapidly improving economics favour Green Ammonia as the emerging and future BAT.[63] China's vast renewable potential and electrolyzer capacity make this pathway increasingly economically feasible relative to coal, especially considering potential future carbon pricing.

3.5.2 | India

India is another major global player, characterized by significant domestic demand primarily for fertilizers (urea being dominant), substantial reliance on imports for both finished fertilizers and feedstocks (ammonia, natural gas), and a mixed conventional production base using natural gas, naphtha, and oil. The average energy efficiency of

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[200] Ammonia in China: change is coming, accessed May 3, 2025

[201] Why China's Renewable Ammonia Market Is Poised for Significant Growth, accessed May 3, 2025

[202] China Emissions Reduction & Energy Conservation Targets for 2024-25, accessed May 3, 2025

Indian plants has improved significantly over decades but still lags behind the best international performers. Emissions intensity reflects this mix, likely averaging above best-practice SMR levels.[203] India's policy landscape strongly favors a shift towards green ammonia. Key drivers include the ambitious Net Zero by 2070 target[204], the National Hydrogen Mission (NHM) aiming for 5 MMTPA of green hydrogen production by 2030[205], and the strategic goal of achieving energy independence by reducing reliance on imported fossil fuels and ammonia.[206]

a. **BAT Analysis for India**:
   i. **Conventional BAT:** Reflects efficient SMR (~1.6 tCO_2/t) and potentially naphtha reforming (~2.5 tCO_2/t),[207] considering the existing feedstock mix. Continuous improvement efforts in the domestic industry are notable.
   ii. **Low-Carbon BAT:** The overwhelming policy push and resource potential point towards **Green Ammonia** as the target BAT. India possesses excellent solar resources, making renewable electricity potentially very cost-effective.[208] The NHM provides strong incentives. Several large-scale green ammonia projects are being developed by companies like ACME and AM Green, often involving retrofits of existing facilities. Blue ammonia is less attractive due to natural gas import dependency and the perceived lower cost of green ammonia in the Indian context, while CCU, using CO_2 from industries like cement for urea production, is seen as a transitional option.[209]

3.5.3 | USA

The US ammonia industry benefits from large domestic natural gas reserves and relatively low gas prices, making SMR the overwhelmingly dominant production technology. The US fleet is generally considered efficient compared to the global average, though improvement potential exists. A significant build-out of new ammonia capacity is planned, largely focused on blue ammonia projects aiming to leverage CCS incentives.[210] The Inflation Reduction Act (IRA) is the defining policy driver, offering substantial tax credits for both low-carbon hydrogen production (45V, tiered based on lifecycle GHG intensity) and carbon capture and sequestration (45Q).[211] This creates

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203 Evaluating Net-zero for the Indian Fertiliser Industry - CEEW, accessed May 3, 2025,

204 India's Long-Term Low-Carbon Development Strategy - UNFCCC, accessed May 3, 2025,

205 Decarbonizing urea production in India via renewable ammonia, accessed May 3, 2025

206 How can India's Fertiliser Sector Adopt Sustainable Green Ammonia? - CEEW, accessed May 3, 2025

207 Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

208 India: a future ammonia energy giant, accessed May 3, 2025

209 Decarbonizing urea production in India via renewable ammonia, accessed May 3, 2025

210 Manufacturers of ammonia plan a boom in the U.S. Will it bust under Trump?, accessed May 3, 2025

211 Decarbonizing Ammonia and Nitrogen Fertilizers with Clean Hydrogen - Open Knowledge Repository - World Bank, accessed May 3, 2025,

strong economic incentives for both blue and green ammonia. The development of regional hydrogen hubs and regulations on methane emissions from the oil and gas sector are also relevant.

a. **BAT Analysis for USA:**
   i. **Conventional BAT:** Efficient SMR (~1.6 tCO_2/t direct) is the standard. Top quartile performers are likely to achieve even lower intensities.[212]
   ii. **Low-Carbon BAT:** The IRA makes both **Blue Ammonia (SMR/ATR + CCS)** and **Green Ammonia** highly competitive and economically feasible. Numerous large-scale blue ammonia projects are proposed, capitalizing on existing gas infrastructure and geological storage potential, incentivized by 45Q.[213] Green ammonia is also strongly incentivized by 45V, particularly attractive in regions with low-cost renewables.[214] ATR technology is also being considered for blue ammonia due to potentially higher capture efficiency and lower costs compared to SMR+CCS. The BAT is therefore rapidly shifting towards pathways that can meet the stringent lifecycle emission thresholds required to maximize IRA tax credits (e.g., <0.45 kg CO_2e/kg H_2 for 45V, implying very low tCO_2e/tNH_3).

3.5.4 | European Union (EU)

The EU has a mature ammonia industry, primarily based on natural gas SMR, with generally high energy efficiency compared to the global average. However, the sector has faced significant challenges recently due to high natural gas prices, leading to production curtailments.[215] The EU's climate policy framework is highly ambitious and directly impacts the ammonia sector. Key elements include the "Fit for 55" package aiming for a 55% GHG reduction by 2030[216], the EU Emissions Trading System (ETS) which covers ammonia production and is phasing out free allowances[217], the Carbon Border Adjustment Mechanism (CBAM) which prices emissions embedded in imported goods like ammonia, and the Renewable Energy Directive (RED) setting targets for renewable fuels of non-biological origin (RFNBOs), including green hydrogen and ammonia, in industry and transport.[218]

a. **BAT Analysis for EU:**

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212 Fourth Greenhouse Gas Study 2020 - International Maritime Organization, accessed May 3, 2025,

213 Manufacturers of ammonia plan a boom in the U.S. Will it bust under Trump?, accessed May 3, 2025

214 Clean Energy 101: Ammonia's Role in the Energy Transition - RMI, accessed May 3, 2025

215 Low-Carbon Ammonia Roadmap (2023-03) - IEAGHG, accessed May 3, 2025

216 Fit for 55 - American Bureau of Shipping, accessed May 3, 2025

217 European Parliament approves EU Emission Trading System reform and new EU Carbon Border Adjustment Mechanism | EY, accessed May 3, 2025

218 Fit for 55: what the EU's 2030 decarbonisation plan means for the hydrogen and ammonia industries - Freshfields Sustainability - blog, accessed May 3, 2025

i. **Conventional BAT:** Defined by the LVIC-AAF BREF, emphasizing energy efficiency (27.6-31.8 GJ/t NH_3) achievable through techniques like heat integration and advanced process control.[219] This likely corresponds to efficient SMR performance (~1.6 tCO_2/t direct).

ii. **Low-Carbon BAT:** Policy strongly favors **Green Ammonia**, driven by RED targets for RFNBOs (which must achieve >70% GHG savings vs. fossil comparator) and potential support mechanisms like the Innovation Fund. [220] Grid-powered electrolysis is becoming viable as grids decarbonize. **Blue Ammonia** is permissible but faces challenges meeting the stringent RFNBO threshold, especially if based on SMR with only process CO_2 capture. ATR or SMR with full flue gas capture might comply but requires CCS infrastructure, available primarily in areas like the North Sea.

3.5.5 | Russia

Russia is a major ammonia producer and exporter, relying almost exclusively on its abundant natural gas resources via SMR technology.[221] Historically, the energy efficiency of Russian plants lagged behind Western Europe, but modernization efforts have been ongoing.[222] Geopolitical events have significantly impacted its export markets, particularly to Europe. Russia has articulated national strategies for low-carbon development and hydrogen. The National Low-Carbon Strategy aims for significant CO_2 reductions by 2050, and the Hydrogen Development Concept sets targets for low-carbon hydrogen production and export, envisioning roles for both blue hydrogen (from gas with CCS) and other low-carbon routes (nuclear, hydro).[223] While domestic climate policies are less stringent than in the EU or US, there is awareness of international market requirements, such as potential carbon border adjustments.[224]

a. **BAT Analysis for Russia:**

i. **Conventional BAT:** Focuses on improving the efficiency of the existing SMR fleet towards international best practices (~1.6 tCO_2/t direct). [225]

ii. **Low-Carbon BAT:** National strategy supports both **Blue Ammonia** (leveraging vast gas reserves and CCS potential) and **Green/Low-Carbon Ammonia** (utilizing nuclear and hydropower resources). Given

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[219] eippcb.jrc.ec.europa.eu, accessed May 3, 2025

[220] European Parliament approves EU Emission Trading System reform and new EU Carbon Border Adjustment Mechanism | EY, accessed May 3, 2025

[221] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[222] Improving resource efficiency in the Russian fertilizer industry through Best Available Techniques, accessed May 3, 2025

[223] Hydrogen Developments | Russia | Global Hydrogen Policy Tracker | Baker McKenzie Resource Hub, accessed May 3, 2025

[224] STRATEGY of socio-economic development of the Russian Federation with low greenhouse gas emissions until 2050 I. Analysis of the - UNFCCC, accessed May 3, 2025

[225] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

the resource base and export focus, Blue Ammonia via SMR/ATR + CCS appears to be the most likely near-to-mid-term BAT pathway.

3.5.6 | Middle East (Saudi Arabia, Qatar, UAE)

The Middle East, particularly Saudi Arabia, Qatar, and the UAE, are significant ammonia producers and exporters, benefiting from low-cost natural gas feedstock and operating generally efficient SMR plants.[226] The region exhibits some of the lowest carbon intensity production globally.[227] Decarbonization efforts are driven by national net-zero targets (varying from 2050 to 2060), economic diversification strategies moving beyond oil and gas, and ambitions to become major hubs for low-carbon hydrogen and ammonia export.[228] The region is actively pursuing both blue and green ammonia pathways. Blue ammonia projects leverage existing gas infrastructure and CCS potential (ATR often favored). Simultaneously, massive investments are being made in green ammonia, capitalizing on world-class solar resources that enable potentially very low production costs.[229] Flagship projects like NEOM in Saudi Arabia (green) and Qatar Energy's planned blue ammonia facility exemplify this dual approach.[230]

a. **BAT Analysis for Middle East:**
   i. **Conventional BAT:** Efficient SMR (~1.6 tCO_2/t direct) is the established baseline, with regional performance already among the world's best.
   ii. **Low-Carbon BAT:** Both **Blue Ammonia (ATR+CCS)** and **Green Ammonia (Electrolysis via Solar PV)** are strong contenders for BAT, driven by resource availability and strategic government/industry investments. The choice may depend on specific project economics and target export markets. BAT benchmarks should reflect the high performance achievable through either pathway in this region.

The following table summarizes the current and future BAT for ammonia production across these regions:

Table 12: Summary of Regional/Country-Specific BAT Analysis

Region/Country	Current Dominant Tech & Avg. Intensity (tCO_2e/t)	Identified Current BAT (Tech & Intensity - tCO_2e/t)	Identified Emerging/ Future BAT (Tech & Intensity - tCO_2e/t)	Indicative Timeframe for Future BAT to become baseline (for new/retrofit plants)	Key Justification Factors	Reference

[226] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[227] Benchmarking the Middle East NOCs against the supermajors - Wood Mackenzie, accessed May 3, 2025

[228] Decarbonization of Oil and Gas in the Gulf Cooperation Council: The Way Forward, accessed May 3, 2025

[229] Hydrogen as a Catalyst for Emissions Reduction in Qatar, accessed May 3, 2025

[230] Global Hydrogen Review 2024: FID doubles, low-emission ammonia takes center stage, accessed May 3, 2025

China	Coal Gasification (High Intensity ~4.4+)	Efficient Coal Gas (~3.8) / SMR (~1.8)	Green Ammonia (<0.5)	2030-2035	Policy (Dual Carbon, NDRC Plan), RE Scale-up, Electrolyzer Capacity	[231]
India	NG/Naphtha SMR (Moderate Intensity ~2.3+)	Efficient SMR/ Naphtha (~1.8-2.5)	Green Ammonia (<0.5)	2030-2035	Policy (Net Zero 2070, NHM), RE Potential (Solar), Energy Security	[232]
USA	NG SMR (Low-Moderate Intensity ~2.1+)	Efficient SMR (~1.8)	Blue Ammonia (SMR/ATR+CCS) (<0.5) / Green Ammonia (<0.5)	Around 2030	Policy (IRA 45V/45Q), Gas Availability, CCS Potential, RE Potential	[233]
EU	NG SMR (Low Intensity ~2.0)	Efficient SMR (~1.8) / BREF Defined	Green Ammonia (<0.8) / Blue Ammonia (ATR+CCS/Full SMR Capture) (<0.8)	Around 2030	Policy (Fit for 55, ETS, RED II, BREF), High Gas Prices, Grid Decarbonization	[234]
Russia	NG SMR (Moderate Intensity ~2.2+)	Efficient SMR (~1.8)	Blue Ammonia (SMR/ATR+CCS) (Low Intensity)	2030-2035	Policy (Hydrogen Strategy), Gas Availability, Export Focus	[235]
Middle East	NG SMR (Low Intensity ~2.0)	Efficient SMR (~1.8)	Blue Ammonia (ATR+CCS) (<0.5) / Green Ammonia (<0.5)	Around 2030 or earlier	Policy (Net Zero Targets, Diversification), Low-Cost Gas, Excellent Solar Resources, Export Hub Ambition	[236]
Canada	NG SMR (Moderate Intensity)	Efficient SMR (~1.8)	Blue Ammonia (West) / Green Ammonia (East/Hydro-rich) (<0.5)	Around 2030s (primarily for export)	Policy (Hydrogen Strategy, ITCs for CCUS/Clean Tech), NG & CCS potential (blue), RE potential (green), export focus, infrastructure development.	
Australia	NG SMR / Coal (varies)	Efficient SMR (~1.8)	Green Ammonia (<0.5)	Around 2030s (primarily for export)	Policy (National Hydrogen Strategy, Net Zero 2050), exceptional RE resources, numerous large-scale green NH3 export projects, international partnerships.	
Indonesia	NG SMR (Moderate Intensity)	Efficient SMR (~1.8)	Green Ammonia / Blue Ammonia (<0.5-0.8)	Phased: mid-to-late 2020s (pilots, specific industries); broader post-2030	Policy (National Hydrogen & Ammonia Roadmap 2025-2060), RE potential, phased targets for	

[231] Low-Carbon Ammonia Roadmap (2023-03) - IEAGHG, accessed May 3, 2025,

[232] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[233] Decarbonizing Ammonia and Nitrogen Fertilizers with Clean Hydrogen - Open Knowledge Repository - World Bank, accessed May 3, 2025

[234] In the future energy system - Hydrogen Europe, accessed May 3, 2025

[235] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025

[236] Ammonia | Industrial Efficiency Technology & Measures, accessed May 3, 2025,

					fertilizer, marine fuel, power co-firing.
Rest of the World (RoW)	Highly Variable (NG SMR, Coal, older tech)	Efficient SMR (~1.8) where applicable	Green Ammonia / Blue Ammonia (Highly Variable) (<0.5-1.0)	Highly variable; pockets, wider consideration post-2030, accelerating 2035-2040	Global decarbonization trends, IMO rules, influence of major economies' policies (e.g., EU CBAM), technology cost reductions, access to finance & tech transfer.

Note: Intensities are indicative cradle-to-gate LCA estimates where possible, otherwise based on direct emissions BAT + typical upstream factor. "<0.5" for Blue/Green reflects potential based on high CCS rates or dedicated renewables, aligned with stringent policy thresholds (e.g., IRA, RFNBO). "<0.8" for EU reflects potential RFNBO threshold alignment.

It is crucial to recognize the dynamic nature of these projections. The indicative timelines presented are based on current information and trends; however, they are subject to change due to a variety of factors. Geopolitical events can shift energy trade patterns and investment priorities. Faster-than-expected technological breakthroughs could accelerate cost reductions, while unforeseen challenges could lead to delays. Evolving market conditions, including fluctuating fossil fuel prices and the actual realized demand for low-carbon ammonia, will also play a significant role. Therefore, continuous monitoring of policy developments, technological progress, and market signals, coupled with adaptive strategies from industry and policymakers, will be essential to navigate this complex transition effectively.

This regional analysis underscores that while efficient SMR represents a global conventional BAT, the transition pathway and the definition of low-carbon BAT are highly dependent on national policies, resource endowments, and economic factors. Policies like the US IRA and the EU's Fit for 55 package are actively shaping the economic feasibility and therefore the BAT landscape, accelerating the shift towards blue and/or green ammonia in those jurisdictions. In contrast, countries like China and India are driven by a combination of climate goals, energy security concerns, and the need to decarbonize large, existing fossil-based industries, leading to strong pushes for green ammonia.

4| FINANCIAL AND ECONOMIC LANDSCAPE

The transition to low-carbon ammonia is fundamentally driven by economic considerations, as new technologies must compete with decades of optimization in conventional production. A detailed financial analysis is essential to understand the current cost landscape, identify key drivers, and assess the viability of future investments.

4.1 | Cost Structure Overview

Understanding the cost components—Capital Expenditure (CAPEX) and Operational Expenditure (OPEX)—is crucial for comparing ammonia production pathways.

a. **Conventional (Grey) Ammonia** production relies on mature and heavily optimized Haber-Bosch and Steam Methane Reforming (SMR) processes. This maturity and widespread deployment result in relatively lower capital costs per unit of production compared to emerging technologies[237].

i. A typical natural gas-based plant (1,220 tonnes per day) might have a total CAPEX of around $665 million, translating to approximately $1,603 per tonne of annual capacity[238]. More competitive projects in the U.S. have seen CAPEX in the range of $900 to $1,200 per tonne of annual capacity.

ii. Operational Expenditure (OPEX) for conventional ammonia is heavily influenced by feedstock prices; natural gas can account for up to 90% of the production costs.[239] Typical fixed costs for a plant are estimated at $100-120 per tonne of NH3.[240]

b. Blue Ammonia combines conventional SMR or Autothermal Reforming (ATR) with Carbon Capture and Storage (CCS).

i. The addition of CCS equipment significantly increases CAPEX, typically by 18% to 79% compared to a base SMR plant, with an additional capital requirement of €40 to €176 million (Q4 2014 estimates).[241] A notable example is the $4 billion project for a 1.1 to 1.4 Mtpa blue ammonia facility (utilizing ATR with CCS) currently under construction in Louisiana.[242]

ii. OPEX also sees an increase of 18% to 33% due to the energy penalty and operational demands of the CCS process.[243] Key cost drivers for blue ammonia include the price of natural gas and the proximity and availability of suitable CO_2 storage sites.

c. Green Ammonia production requires substantial upfront investment (CAPEX) in renewable energy infrastructure (such as wind farms and solar panels) and electrolysers.

i. Electrolyzer CAPEX varies significantly by technology and scale, ranging from approximately $700 to $2,450 per kilowatt (kW) for alkaline and PEM technologies. [244] For a large-scale 1 Mtpa green ammonia plant, the

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[237] Ammonia production cost breakdown - ResearchGate, accessed June 10, 2025

[238] Ammonia plant cost comparisons: Natural gas, Coal, or Electrolysis?, accessed June 10, 2025

[239] Ammonia and its prospects, www.gasworld.com, accessed June 10, 2025,

[240] The Cost of CO2-free Ammonia, accessed June 10, 2025

[241] Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS - IEAGHG, accessed June 10, 2025,

[242] CF Industries Announces Joint Venture with JERA Co., Inc., and Mitsui & Co., Ltd., for Production and Offtake of Low-Carbon Ammonia, accessed June 10, 2025,

[243] Techno - Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS - IEAGHG, accessed June 10, 2025

[244] Ammonia production cost breakdown - ResearchGate, accessed June 10, 2025

required 1.5 GW of electrolyzers could entail a CAPEX of around $6.5 billion.[245]

ii. Operational Expenditure (OPEX) for green ammonia is dominated by electricity costs, which can constitute up to 61% of total costs.[246] Other OPEX components include water supply (for electrolysis), maintenance, labor, and transportation.

A fundamental observation in the decarbonization of ammonia production is the "CAPEX vs. OPEX shift." Conventional ammonia production is inherently OPEX-heavy, with its economic viability largely dictated by the volatile price of fossil fuel feedstocks, particularly natural gas, which can represent a dominant portion of its operating costs. In contrast, green ammonia production fundamentally shifts this cost burden towards upfront capital investment in renewable energy generation and electrolyzer capacity, making it a CAPEX-heavy endeavor. This shift implies a different risk profile for investors: while the initial investment for green ammonia is substantially higher, it offers greater long-term price stability by decoupling production costs from the volatility of fossil fuel markets. However, this also necessitates robust financing mechanisms and a long-term commitment of capital to realize the benefits of reduced operational risk and environmental impact.

4.2 | Comparative Levelized Cost of Ammonia (LCOA)

The Levelized Cost of Ammonia (LCOA) provides a comprehensive metric for comparing the total cost of producing ammonia over a plant's lifetime, taking into account all capital and operating expenses.

a. **Grey Ammonia:** Production costs for grey ammonia vary widely depending on regional energy costs, ranging from approximately $100 to $1,000 per tonne, with an average of $305 per tonne since 2013.[247] A typical pre-shipment cost for ammonia produced from natural gas at $3.00/MMBtu is around $200 per tonne. [248]

b. **Blue Ammonia:** The LCOA for blue ammonia is estimated to be around $300 per tonne, assuming a natural gas price of $3.00/MMBtu and the inclusion of CCS costs. [249] Blue ammonia is currently considered less expensive than green ammonia, carrying an estimated cost premium of approximately 40% over conventional (grey) ammonia. Some analyses estimate blue ammonia LCOA at

[245] H2 Global Energy: renewable ammonia production in the MENA region, accessed June 10, 2025

[246] Green Ammonia Production with Nuclear Power - Zetomica Energy, accessed June 10, 2025,

[247] Scaling Up Hydrogen: The Case for Low- Carbon Ammonia - Bloomberg Professional Services, accessed June 10, 2025,

[248] The Cost of CO2-free Ammonia, accessed June 10, 2025

[249] The Cost of CO2-free Ammonia, accessed June 10, 2025

around €0.417/kg (approximately $450/tonne).[250] Projections suggest that blue ammonia could become more cost-effective than grey ammonia in key regions within the next four years, driven by increasing carbon costs for conventional production.[251]

c. **Green Ammonia:** Currently, green ammonia production costs are significantly higher, ranging from $600 to $1,200 per tonne. [252] In 2022, IRENA estimated costs between $720 and $1,400 per tonne.[253] A 2020 study identified an achievable LCOA of $473 per tonne at optimal locations.[254] However, these costs are projected to fall substantially. By 2030, the LCOA for green ammonia is predicted to decrease to $310-$350 per tonne.[255] BloombergNEF forecasts that green ammonia could become cheaper in over half of the 29 markets modeled by 2034.[256]

d. **Cost Premiums for Low-Carbon Alternatives:** Green ammonia currently commands a significant cost premium, estimated to be anywhere from 10% higher to more than double, or even up to six times higher, compared to grey ammonia, depending on underlying assumptions. Other sources indicate it is 2 to 3 times more expensive than regular ammonia.[257] Blue ammonia generally carries a cost premium of about 40% over conventional grey ammonia.

Table 13:Comparative Ammonia Production Costs (Current & Projected LCOA)

Pathway	Current LCOA Range (USD/tonne)	Projected LCOA 2030-2035 (USD/tonne)	Current Cost Premium over Grey (approx.)	Key Cost Drivers
Conventional (Grey) Ammonia	$100 - $1,000 (Avg. $305)	N/A (Baseline)	N/A	Natural gas price (up to 90% of cost), Coal price, Plant efficiency
Blue Ammonia (SMR/ATR + CCS)	~$300 - $530	~$250 - $400 (projected to be cheaper than grey by 2026 in EU with ETS)	~40%	Natural gas price, CO2 capture/compression/storage costs, Upstream methane emissions

[250] Blue Hydrogen in a flexible multicommodity energy system for ammonia production, accessed June 10, 2025

[251] Blue ammonia nears cost viability but green to stay pricey - CRU Group, accessed June 10, 2025

[252] Ammonia production cost breakdown - ResearchGate, accessed June 10, 2025

[253] Ammonia's Potential Role in a Low-Carbon Economy - Congress.gov, accessed June 10, 2025,

[254] Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production - RSC Publishing, accessed June 10, 2025

[255] Green Ammonia – An Alternative Fuel - FutureBridge, accessed June 10, 2025,

[256] Scaling Up Hydrogen: The Case for Low- Carbon Ammonia - Bloomberg Professional Services, accessed June 10, 2025,

[257] Can ammonia propel the shipping industry toward a zero-carbon future?, accessed June 10, 2025

Green Ammonia (Electrolysis + RE)	\$600 - \$1,400	\$310 - \$350	10% to >200% (2x-6x)	Renewable electricity price, Electrolyzer CAPEX, Intermittency management

Note: LCOA values are indicative and depend on specific project parameters, regional energy prices, and financing structures. Projections are subject to technological advancements and policy support.

4.3 | Investment Viability and Returns

Assessing the investment viability of low-carbon ammonia projects involves examining typical Return on Investment (ROI) and Payback Periods, alongside the financial scale of major announced initiatives.

For green ammonia projects, various techno-economic analyses offer insights into potential returns. An optimal system configuration in Denmark, for instance, achieved an LCOA of \$103.79 per tonne with a total CAPEX of approximately \$501.5 million and annual OPEX of \$9.69 million.[258] For electrochemical ammonia synthesis, profitability metrics have included an ROI of 8%, a Net Present Value (NPV) of \$40 million, and a payback period ranging from 4 to 6 years.[259] Another study indicated that a wind-powered ammonia project could be technically and economically feasible with an NPV of €77.4 million and a payback period of 7.62 years.[260]

Major announced projects underscore the significant capital requirements for scaling low-carbon ammonia production. The NEOM Green Hydrogen Project in Saudi Arabia, a flagship green ammonia initiative, represents a total investment of \$8.4 billion, with its Final Investment Decision (FID) announced in May 2023. Construction on this project is reportedly 80% complete, with commercial operations targeted for 2027. Similarly, the CF Industries / Mitsui / JERA blue ammonia project in Louisiana, USA, is estimated to cost \$4 billion for a 1.1 to 1.4 Mtpa facility, with FID announced in April 2025 and production planned to commence in 2029. The ACME Green Ammonia Project in Duqm, Oman, has secured financing for its first phase (0.1 Mtpa) and has begun construction, targeting commercial operation by Q1 2027.

Despite these large-scale announcements, a notable observation is the "investment chasm" that exists between ambition and reality in the low-carbon ammonia sector. While there is a vast pipeline of announced low-carbon ammonia projects, totaling hundreds of millions of tonnes in potential capacity, only a small fraction—approximately 4%—of this announced capacity has reached FID or commenced construction. This substantial gap suggests that converting project ambition into operational assets faces considerable hurdles. The primary reasons for this include the high perceived risk for investors due to cost uncertainties, the difficulty in securing firm, long-term offtake agreements, and broader macroeconomic factors such as

[258] Techno-Economic Analysis of Renewable Energy-Powered Ammonia Production, accessed June 10, 2025

[259] Techno-economic analysis and life cycle assessment for electrochemical ammonia production using proton conducting membrane - OSTI, accessed June 10, 2025

[260] Directing the wind: Techno-economic feasibility of green ammonia for farmers and community economic viability - Frontiers, accessed June 10, 2025

elevated inflation and tight global liquidity that have prevailed since 2022. This implies that overcoming this investment chasm necessitates comprehensive de-risking strategies that extend beyond mere technological readiness. These strategies must include robust, long-term policy support (e.g., subsidies, mandates, carbon pricing), the establishment of bankable offtake agreements (which current floating price markets do not readily accommodate), and potentially innovative financing models designed to reduce the risk premium for investors.

Table 14: Key Financial Metrics for Low-Carbon Ammonia Projects (CAPEX, OPEX, ROI, Payback Period)

Metric	Conventional (Grey) Ammonia	Blue Ammonia	Green Ammonia
Typical CAPEX (USD/tonne annual capacity)	$900 - $1,603	$1,600 - $2,900 (based on 40-79% premium over grey)	$2,370 - $6,500 (incl. RE & electrolyzers)
Major OPEX Components	Natural gas (up to 90%), fixed costs ($100-120/tonne)	Natural gas, CCS operation (18-33% increase over SMR OPEX)	Electricity (up to 61%), water, maintenance, labor
Example Project Investment (Total)	N/A (mature, often retrofits)	CF Industries/Mitsui/JERA: $4 billion (1.1-1.4 Mtpa)	NEOM: $8.4 billion (1.2 Mtpa)
Typical ROI (%)	Established, market-dependent	Data emerging, often tied to policy incentives	Data emerging, often tied to policy incentives
Typical Payback Period (years)	Established, market-dependent	Data emerging, often tied to policy incentives	Data emerging, often tied to policy incentives

Note: CAPEX figures for green ammonia include associated renewable energy generation and electrolyzer costs. Financial metrics are indicative and highly sensitive to specific project details, regional factors, and policy support.

4.4 | Sensitivity Analysis of Key Financial Drivers

The economic viability of low-carbon ammonia production is highly sensitive to several key market and policy variables.

a. **Impact of Natural Gas Price Fluctuations:** For conventional and blue ammonia, the price of natural gas is a dominant factor. Natural gas can account for up to 90% of the production costs for conventional SMR-based ammonia. Historical data demonstrates that volatile and upward trends in natural gas prices directly lead to significant increases in ammonia prices and can impact production volumes.[261] Blue ammonia costs are also highly sensitive to natural

[261] Impact of Rising Natural Gas Prices on U.S. Ammonia Supply - ers.usda.gov, accessed June 10, 2025

gas prices, in addition to CO_2 storage proximity. This dependence on fossil fuel price volatility represents a significant risk for both conventional and blue ammonia producers.

b. **Sensitivity to Renewable Electricity Prices and Electrolyzer CAPEX:** For green ammonia, the Levelized Cost of Electricity (LCOE) from renewable sources and the Capital Expenditure (CAPEX) of electrolyzers are the most influential cost components. Electricity can constitute up to 61% of the total OPEX for green ammonia production.[262] For green ammonia to be competitive with blue ammonia, a LCOE of approximately $35/MWh or lower is often required.[263] Furthermore, external factors like tariffs on electrolyzers and renewable energy components can increase green ammonia production expenses by 15% to 20%.[264] This highlights the critical need for continued cost reductions in renewable energy generation and electrolyzer manufacturing.

c. **Influence of Carbon Pricing Mechanisms and Policy Incentives:** Policy interventions are consistently identified as the most critical factor in bridging the cost gap and making low-carbon ammonia projects financially viable.

    i. **Carbon Pricing:** Implementing a carbon tax can significantly alter the economic landscape. A carbon tax of $50 per tonne of CO_2, for instance, could make green ammonia competitive with conventional production by 2030.[265] Some analyses suggest that a carbon price of around $100 per tonne of CO_2 would be necessary by the early 2030s to achieve significant adoption of low-carbon fuels.[266]

        i. **U.S. Inflation Reduction Act (IRA):** The IRA offers substantial tax credits, notably the 45V production tax credit for clean hydrogen, which can provide up to $3 per kilogram for the lowest emissions tier.[267] This credit has the potential to reduce electrolysis-based hydrogen costs from $5-$7/kg to $2-$4/kg. For blue hydrogen, the 45V credit can offer $0.60-$0.75/kg. The 45Q tax credit for carbon capture and sequestration also provides significant financial incentives. These incentives can render low-carbon ammonia competitive with, or even cheaper than,

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[262] Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production - RSC Publishing, accessed June 10, 2025

[263] A comparative techno-economic assessment of blue, green, and hybrid ammonia production in the United States - RSC Publishing, accessed June 10, 2025

[264] US Tariff Impact on Green Ammonia Industry – Markets and Markets, accessed June 10, 2025

[265] Techno-economic viability of islanded green ammonia as a carbon-free energy vector and as a substitute for conventional production - RSC Publishing, accessed June 10, 2025

[266] Can ammonia propel the shipping industry toward a zero-carbon future?, accessed June 10, 2025

[267] Understanding 45V and Clean Hydrogen's Importance to U.S. Energy Leadership - CSIS, accessed June 10, 2025

unabated grey ammonia. However, the potential termination of the 45V credit for projects starting construction after December 2025 introduces significant policy uncertainty and risk.[268]

ii. **EU Hydrogen Bank:** This initiative provides fixed premium payments, ranging from €0.20 to €1.88 per kilogram of renewable hydrogen, to bridge the price difference between production costs and market prices.[269] This financial support is crucial for accelerating the deployment of renewable hydrogen and its derivatives, including green ammonia, despite their higher initial costs.

A fundamental observation is that policy acts as the "primary lever" for the economic viability of low-carbon ammonia. The inherent raw economic viability of low-carbon ammonia is currently challenged by significantly higher costs compared to conventional methods. However, consistent evidence demonstrates that policy interventions—such as tax credits, direct subsidies, and carbon pricing mechanisms—are the most critical factors in bridging this cost gap and making projects financially viable. Without such support, many projects would likely not proceed. This underscores that the transition to low-carbon ammonia is not purely a market-driven evolution but a policy-driven transformation. The stability and long-term commitment of these policies are paramount for attracting the necessary multi-billion dollar investments and de-risking projects. Any policy uncertainty, such as the potential repeal of the 45V tax credit in the U.S., poses a significant threat to project development and the pace of decarbonization.

5| POLICY AND COMPLIANCE FRAMEWORKS

The successful transition to a low-carbon ammonia industry is inextricably linked to robust policy and compliance frameworks. These frameworks provide the necessary incentives, regulatory certainty, and long-term vision to guide investment and ensure that decarbonization efforts align with global climate objectives.

5.1 | International Climate Frameworks and Compliance

International climate frameworks, particularly the UNFCCC Article 6 based mechanisms, play a pivotal role in shaping the decarbonization trajectory of industrial sectors like ammonia production.

A critical observation in the context of climate investment is the "temporal mismatch" between industrial asset lifetimes and climate targets. Industrial assets, such as ammonia plants, are designed for long operational lifetimes, often spanning 20 to 50 years or more. However, global climate targets, particularly the ambition for net-zero

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268 Hydrogen cracked from imported green ammonia could be cheaper in Europe than EU-made green H2: BNEF, accessed June 10, 2025

269 Nearly €1 billion awarded to boost development of renewable hydrogen - European Union, accessed June 10, 2025

emissions by mid-century, necessitate rapid and deep decarbonization within a much shorter timeframe. This creates a fundamental temporal mismatch where significant investments made today, particularly in transitional technologies like blue ammonia with imperfect carbon capture, could become misaligned with future, more stringent climate goals as the world progresses towards net-zero. This implies a need for a highly forward-looking approach to investment decisions, prioritizing technologies that are genuinely compatible with a net-zero future, even if they present higher initial costs, potentially favoring technologies that can achieve near-zero emissions over their entire lifespan, even if they are currently more expensive, often pointing towards green ammonia as the ultimate long-term solution. Furthermore, it highlights the inherent risk of stranded assets for technologies that cannot adapt to evolving environmental standards or that rely on residual emissions incompatible with ultimate climate objectives.

5.2 | Regional and National Policy Landscapes

The global landscape for low-carbon ammonia development is profoundly shaped by diverse regional and national policy frameworks. These policies provide the impetus and financial incentives for the transition.

a. **U.S. Inflation Reduction Act (IRA):** The IRA is a defining policy driver in the U.S., offering substantial production tax credits, such as the 45V credit for clean hydrogen and the 45Q credit for Carbon Capture, Utilization, and Storage (CCUS). This has spurred a significant surge in both blue and green ammonia project activity, with the U.S. targeting 10 million tonnes per year of clean hydrogen production by 2030. [270]
b. **European Union (EU) Framework:** The EU's ambitious climate policy framework, including the "Fit for 55" package, aims for a 55% GHG reduction by 2030. The REPowerEU plan sets a target of 20 million tonnes per year of hydrogen by 2030. Key elements impacting ammonia include binding targets for Renewable Fuels of Non-Biological Origin (RFNBOs) under the revised Renewable Energy Directive (RED III), which mandates that at least 42% of hydrogen used in industry must come from renewable sources by 2030. The EU Emissions Trading System (ETS) covers ammonia production, and the Carbon Border Adjustment Mechanism (CBAM) prices embedded emissions in imported goods. The European Hydrogen Bank further supports projects through competitive auctions.
c. **China's Dual Carbon Goals:** China, the world's largest ammonia producer, has committed to "dual carbon" goals: peaking CO_2 emissions before 2030 and achieving carbon neutrality by 2060. The National Development and Reform Commission (NDRC) has a plan to reduce ammonia industry CO_2 emissions by 13 million tonnes by 2025 through efficiency upgrades. China is actively promoting green hydrogen and ammonia, leveraging its massive renewable energy deployment and world-leading electrolyzer manufacturing capacity.

[270] Understanding 45V and Clean Hydrogen's Importance to U.S. Energy Leadership - CSIS, accessed June 10, 2025

d. **India's National Hydrogen Mission (NHM):** India's ambitious Net Zero by 2070 target is supported by the NHM, which aims for 5 Mtpa of green hydrogen production by 2030. India's policy strongly favors green ammonia due to its excellent solar resources and strategic energy independence goals.

e. **Australia's National Hydrogen Strategy:** Australia aims to become a global leader in green hydrogen production and export, targeting 0.5 Mtpa by 2030 and 15 Mtpa by 2050. The Hydrogen Headstart program provides production credits to support large-scale renewable hydrogen projects.

The consistency of these projects with Nationally Determined Contributions (NDCs) and Long-Term Low Emission Development Strategies (LT-LEDS) is a key compliance consideration. While many countries are developing national hydrogen strategies, their full integration into official LT-LEDS submitted to the UNFCCC is an ongoing process.

Table 15:Identified Ammonia Producing Countries, Net-Zero Targets, and Official Sources

Country	2024e Ammonia Production ('000 tonnes) [271] / Status	Net-Zero Target Year (YNetZero)	Official Source for Target (Source Type from or other specified)	Scope of Net-Zero Target (e.g., All GHGs/CO2 only, Legal Status & Snippet ID from or other specified)
China	47,000	2060 (Before 2060)	(Govt. plans, LTS to UNFCCC)	CO_2 only (LTS), Policy Document
United States	14,000	2050	(Federal Sustainability Plan, Govt. goals)	All GHGs (economy-wide), Policy Goal/Executive Order
Russia	14,000	2060	(LTS to UNFCCC)[272] (Net Zero Tracker)	All GHGs, In Law (Govt. Order approving LTS)
India	15,000	2070	[1] (COP26 announcement, LTS to UNFCCC)	Net-Zero (implies all GHGs), Policy Document
Indonesia	6,000	2060 (or sooner)	[8] (LT-LEDS to UNFCCC)	Net-zero emissions (implies all GHGs), Policy Document (LT-LEDS)
Saudi Arabia	5,400	2060	[1] (Govt. announcement net zero by 2060)	Net Zero (implies all GHGs), Policy Document
Egypt	5,000	Not Found	[1] (No official Net Zero Target year submitted to UNFCCC)	N/A
Iran	4,200	Not Found	[9] (No net zero target, no LTS submitted)	N/A
Canada	3,600	2050	[1] (Canadian Net-Zero Emissions Accountability Act)	All GHGs, In Law
Pakistan	3,500	Not Found	[10] (NDC targets vs BAU, no explicit net-zero year)	N/A

[271] Nitrogen (fixed)—ammonia - Mineral Commodity Summaries 2024 - USGS.gov, accessed June 7, 2025

[272] Russian Federation (Country) | Net Zero Tracker, accessed June 7, 2025,

Trinidad & Tobago	3,200	Not Found	[1] (No explicit Net Zero target year; NDC for 2030)	N/A
Qatar	3,100	Not Found	[12] (No net zero target; NDC vs BAU)	N/A
Algeria	2,000	Not Found	[14] (No net zero target, no LTS submitted to UNFCCC as of Feb 2024)	N/A
Netherlands	2,000	2050	[1] (Climate Law, Govt. commitment)	All GHGs, In Law
Nigeria	1,700	2060	[15] (LT-LEDS to UNFCCC)	Net-zero emissions (all sectors), Policy Document (LT-LEDS)
Oman	2,000	2050	[1] (Reference to national strategy for carbon neutrality by 2050)	Carbon Neutrality (implies all GHGs), Policy Document (National Strategy)
Germany	1,700	2045	[1] (Climate Change Act, Climate Law)	All GHGs, In Law
Poland	1,600	2050	[17] (EU Climate Law, National Energy and Climate Plan alignment)	All GHGs (EU Target), In Law (EU Level)
Australia	1,300	2050	[1] (NDC, National Hydrogen Strategy)	All GHGs, Policy Document (NDC) [1]
Uzbekistan	1,300	Not Found	[19] (General regional pledges 2050-2060, no specific official YNetZero submitted to UNFCCC)	N/A
Vietnam	1,400	2050	[22] (COP26 Pledge, National Climate Change Strategy)	Net Zero (implies all GHGs), Policy Document/Pledge
Malaysia	1,400	2050	[24] (Govt. commitment, policy statements)	Net Zero Carbon (implies all GHGs), Policy Document/Pledge
Denmark	N/A (Prospective)	2045	[1] (Govt. announcement, Climate Act newer ambition)	All GHGs, 2050 in law, 2045 proposed
Norway	N/A (Prospective)	2050	[1] (Climate Change Act goal)	All GHGs, Policy Goal
Japan	N/A (Prospective)	2050	[1] (Govt. declaration, NDC)	All GHGs, Policy Document
Chile	N/A (Prospective)	2050	[1] (Climate Law commitment)	All GHGs (Carbon Neutrality), In Law
Brazil	N/A (Prospective)	2050	[1] (NDC submission, Govt. pledge)	All GHGs (Climate Neutrality), Policy Document (NDC)
UAE	N/A (Prospective)	2050	[1] (Net Zero by 2050 strategic initiative)	Net Zero (implies all GHGs), Policy Document/Strategic Initiative
Morocco	N/A (Prospective)	2050	[1] (LT-LEDS goal, National Sustainable Development Strategy)	Carbon Neutrality (implies all GHGs), Policy Document
Namibia	N/A (Prospective)	Not Found	[1] (NDC target for 2030, no explicit net-zero year)	N/A
South Africa	N/A (Prospective)	2050	[1] (LTS goal, Just Transition Framework)	CO_2 or All GHGs, Policy Document (LTS) [1]

Note on YNetZero: For China, "Before 2060" is interpreted as 2060. For Indonesia, "2060 or sooner" is interpreted as 2060. Countries identified as "Prospective" included regardless of their current large-scale production volumes to reflect their potential role in green ammonia development; their production is marked N/A (Prospective [1]) if not listed *in USGS data.[3] For Oman, the 2050 target is based on references to a national strategy within project descriptions from the initial analysis.[1] Poland's 2050 target is in the context of EU-level commitments.[17] Nigeria's 2060 target is from its LT-LEDS submitted to UNFCCC.[15] Russia's 2060 target is from its LTS submitted to UNFCCC.[6] Indonesia's 2060 target is from its LT-LEDS.[8] Vietnam's 2050 target is from its COP26 pledge and strategy.[22] Malaysia's 2050 target is from government commitments.[24] Iran, Pakistan, Qatar, Algeria, Uzbekistan, Egypt, Namibia, and Trinidad & Tobago do not have clearly defined economy-wide net-zero target years suitable for the formula based on available information.[9]*

A significant observation is the emergence of a "policy patchwork" across different regions, and its profound impact on global competitiveness. Various regions have adopted distinct policy approaches to drive low-carbon ammonia development. For instance, the U.S., with its IRA tax credits, supports both blue and green pathways, while the EU, through its stringent RFNBO mandates, strongly favors green ammonia. China and India, driven by energy security and decarbonization goals, are also pushing for green ammonia development. This varied policy landscape, rather than a uniform global framework, creates differential economic incentives and competitive environments. This directly influences where projects are developed and can potentially lead to trade distortions.

6| BENCHMARK EMISSION FACTORS

Based on the preceding analysis of global performance and regional BAT assessments, this section proposes specific benchmark emission factors for ammonia production. These benchmarks aim to reflect achievable performance based on BAT, consider regional contexts, and provide a basis for driving decarbonization efforts, potentially within frameworks of the Paris Agreement or national regulatory schemes. The proposed benchmarks are presented on a cradle-to-gate Life Cycle Assessment (LCA) basis where data allows, acknowledging that system boundaries and LCA methodologies can introduce variability. Where LCA data is sparse or highly variable, benchmarks may lean more heavily on direct emission BAT values plus a standardized estimate for upstream emissions.

6.1 | Proposed Benchmarks

Given the significant regional variations identified, a single global benchmark is deemed inappropriate. Instead, regionally differentiated benchmarks are proposed to reflect current best practices.

Table 16: Recommended Benchmark Emission Factors (tCO_2e/tNH_3, Cradle-to-Gate LCA)

Region/Country	Benchmark Type	BAT Pathway Reflected	Direct Emissions (tCO_2e/tNH_3)	Upstream Emissions (tCO_2e/tNH_3)	Indicative LCA Benchmark (tCO_2e/tNH_3)	Basis/Justification
Global Reference	Standard	Efficient SMR (NG)	~1.6	~0.6	~2.2	Global conventional BAT direct + typical NG upstream
China	Standard	Efficient Coal Gas	~3.8	~1.3	~5.1	Reflects BAT for dominant regional tech + est. upstream coal
India	Standard	Efficient SMR/Naphtha	~1.8	~0.7	~2.5	Reflects efficient reforming BAT + est.

						upstream (NG/Naphtha blend)
USA	Standard	Efficient SMR (NG)	~1.6	~0.6	~2.2	Reflects efficient SMR BAT + typical NG upstream
EU	Standard	Efficient SMR (NG) / BREF	~1.6	~0.6	~2.2	Reflects efficient SMR BAT / BREF + typical NG upstream
Russia	Standard	Efficient SMR (NG)	~1.6	~0.6	~2.2	Reflects efficient SMR BAT + typical NG upstream
Middle East	Standard	Efficient SMR (NG)	~1.6	~0.6	~2.2	Reflects efficient SMR BAT + typical NG upstream

Notes: Values are indicative. Direct emissions reflect BAT performance for the specified pathway. Upstream emissions are estimates based on typical values (e.g., ~0.6 tCO_2e/t for NG SMR, ~1.3 tCO_2e/t for Coal Gas [1], ~0.4-0.9 tCO_2e/t for Blue/Green pathways reflecting methane leakage/CCS energy or embodied emissions in RE/electrolyzers). LCA Benchmark is the sum of Direct + Upstream

6.2 | Justification

The proposed benchmarks are derived from the BAT analysis in Section above:

a. **Standard Benchmarks[62]:** These generally reflect the performance of efficient natural gas SMR (~1.6 tCO_2/t direct + upstream estimate ≈ 1.8 tCO_2e/t LCA), which represents the most widespread and generally most efficient conventional technology globally. For China, the standard benchmark acknowledges the current dominance and BAT level of coal gasification (~3.8 tCO_2/t direct + upstream ≈ 4.0 tCO_2e/t LCA) as a starting point. For India, it reflects a blend closer to efficient gas/naphtha reforming. These standard benchmarks are set below current regional averages, thereby incentivizing the adoption of existing best practices and efficiency improvements across the fleet.

   The use of LCA (cradle-to-gate) benchmarks is preferred as it provides a more holistic view of emissions, including critical upstream impacts like methane leakage or electricity grid emissions. However, consistency in LCA methodology and data availability remains a challenge. Where benchmarks rely heavily on direct emissions BAT (e.g., 1.6 tCO_2/t for SMR), a standardized, conservative factor should be added to account for typical upstream emissions until more robust regional LCA data becomes widely available. Conservativeness principles should guide benchmark setting, especially where data is uncertain.

7| SELECTION OF BEST AVAILABLE TECHNOLOGY (BAT)

7.1 | Selection Criteria

Based on the comprehensive comparative analysis, the Best Available Technology (BAT) is selected by identifying the technology that rigorously satisfies four key criteria: Economic Viability, Environmental Soundness, Regulatory Compliance, and Technical Feasibility.

- **Economic Viability:** The chosen technology must demonstrate the lowest Levelized Cost of Ammonia (LCOA) under the prevailing carbon pricing scenario, considering both Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), as well as its payback period and Return on Investment (ROI).[1]

- **Environmental Soundness:** It must exhibit the lowest Greenhouse Gas (GHG) emissions intensity (tonnes CO_2 per tonne NH_3) and the highest energy efficiency (GJ per tonne NH_3), while also considering resource use, waste generation, and byproduct management.[1]
- **Regulatory Compliance:** The technology must meet or exceed all applicable national environmental and safety standards, and be compatible with international agreements such as the Paris Agreement and national net-zero targets.[1]
- **Technical Feasibility:** It must be proven at a commercial scale, possess a suitable Technology Readiness Level (TRL), and be compatible with existing or readily available infrastructure, ensuring operational reliability and manageable maintenance requirements.[1]

7.2 | Decision for BAT Selection (Paragraph 7.1.9 of the GS4GG Methodology)

A specific decision rule applies when evaluating two candidate technologies that each meet a different set of the primary criteria. If one technology satisfies the criteria for Economic Viability (1), Regulatory Compliance (3), and Technical Feasibility (4), and another technology satisfies the criteria for Environmental Soundness (2), Regulatory Compliance (3), and Technical Feasibility (4), then the technology with the **lowest GHG emissions** shall be chosen. This requirement explicitly prioritizes environmental performance (lowest GHG emissions) when economic viability and environmental soundness are the differentiating factors between two otherwise compliant and feasible technologies. This ensures that the selection process consistently drives towards the most climate-aligned outcome.

Table 17: BAT Selection Criteria Compliance for Identified Emerging/Future BAT

Region/ Country	Identified Current BAT (Tech & Intensity - tCO2e/t)	Economic Viability Compliance	Environmental Performance Compliance	Regulatory Compliance	Technical Feasibility Compliance	Social and Strategic Factors
Global	Efficient SMR (NG) (~1.6 tCO2/t)	Generally established, but varies with feedstock price.	Achieves ~1.6 tCO2/tNH3 direct, significant gap from average.	Meets national environmental regulations.	Mature and widely deployed.	Energy security, job creation, economic diversification.
China	Efficient Coal Gas (~3.8 tCO2/t) / SMR (~1.8 tCO2/t)	Economically viable as it represents an improvement over the average existing fleet.	Represents improvement over average.	Aligns with regulatory compliance for efficiency upgrades.	Technically feasible due to mature technologies.	Energy security, reduced pollution.
India	Efficient SMR (~1.8 tCO2/t) and Naphtha reforming	Economically viable as established technologies.	Continuous improvement efforts.	Aligns with regulatory compliance for continuous improvement.	Technically feasible as established technologies.	Energy security, import reduction.

	(~2.5 tCO_2/t)					
USA	Efficient SMR (~1.8 tCO_2/t)	Economically viable given natural gas availability.	Offers better environmental performance than the global average.	Meets existing regulatory standards.	Technically feasible due to the mature and efficient US fleet.	Energy security, job creation.
EU	Efficient SMR (~1.8 tCO_2/t) / BREF Defined	Economically viable as an established industry.	High energy efficiency compared to global average.	Aligns with regulatory compliance under the Industrial Emissions Directive (IED) and its BAT Reference documents (BREFs).	Technically feasible as an established industry.	Energy security, industrial competitiveness.
Russia	Efficient SMR (~1.8 tCO_2/t)	Economically viable due to abundant natural gas resources.	Modernization efforts ongoing.	Less stringent domestic climate policies, but awareness of international market requirements.	Technically feasible due to abundant natural gas resources.	Leveraging existing gas resources for export.
Middle East (KSA, QAT, UAE)	Efficient SMR (~1.8 tCO_2/t)	Economically viable due to low-cost gas.	Already demonstrates low environmental impact.	Aligned with national net-zero targets (varying).	Technically feasible due to efficient plants.	Ambition to become an export hub.
Canada	Efficient SMR (~1.8 tCO_2/t)	Economically viable due to natural gas availability.	Efficient SMR.	Aligns with national Hydrogen Strategy.	Technically feasible due to natural gas availability.	Export focus; leveraging diverse resources.
Australia	Efficient SMR (~1.8 tCO_2/t)	Economically viable due to natural gas availability.	Efficient SMR.	Aligns with National Hydrogen Strategy.	Technically feasible due to natural gas availability.	Export focus; development of green metals. [1]
Indonesia	Efficient SMR (~1.8 tCO_2/t)	Economically viable due to the availability of natural gas.	Efficient SMR.	Aligns with National Hydrogen & Ammonia Roadmap.	Technically feasible due to the availability of natural gas.	Energy security; use for fertilizer and marine fuel.
Rest of the World (RoW)	Efficient SMR (~1.8 tCO_2/t) where applicable	Economically viable in many regions.	Represents best available conventional technology.	Influenced by global decarbonization trends and major economies' policies.	Technically feasible in many regions.	Maintaining market access; competitive pressures.

8| CONCLUSIONS AND RECOMMENDATIONS

This analysis, conducted in line with Section 7.1, Option 1: Best Available Technology (BAT) of the methodology for "Green Ammonia Production," provides a determination of the Best Available Technology for ammonia production at global, regional, and country levels. The assessment rigorously applied criteria of economic viability, environmental performance, regulatory compliance, and technical feasibility to identify the most appropriate BAT for each context.

8.1 | Outcome of Best Available Technology (BAT) Determination

Based on the detailed comparative analysis, the identified Best Available Technology (BAT) for ammonia production in various geographies is as follows:

- **China:** The current BAT is **Efficient Coal Gasification (~3.8 tCO2/t)** or **Efficient SMR (~1.8 tCO2/t)**. These technologies are technically feasible and economically viable as they represent improvements over the average existing fleet, aligning with regulatory compliance for efficiency upgrades.
- **India:** The current BAT is **Efficient SMR (~1.8 tCO2/t)** and **Naphtha reforming (~2.5 tCO2/t)**. These are established technologies that are technically feasible and economically viable, aligning with regulatory compliance for continuous improvement.
- **USA:** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible due to the mature and efficient US fleet and economically viable given natural gas availability, meeting existing regulatory standards.
- **European Union (EU):** The current BAT is **Efficient SMR (~1.8 tCO2/t)** or as defined by **BREF**. This is technically feasible and economically viable as an established industry, aligning with regulatory compliance under the Industrial Emissions Directive (IED) and its BAT Reference documents (BREFs).
- **Russia:** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible and economically viable due to abundant natural gas resources, with ongoing modernization efforts.
- **Middle East (KSA, QAT, UAE):** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible due to efficient plants and economically viable due to low-cost gas, already demonstrating low environmental impact.
- **Canada:** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible and economically viable due to natural gas availability.
- **Australia:** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible and economically viable due to natural gas availability.
- **Indonesia:** The current BAT is **Efficient SMR (~1.8 tCO2/t)**. This is technically feasible and economically viable due to the availability of natural gas.
- **Rest of the World (RoW):** The current BAT is **Efficient SMR (~1.8 tCO2/t)** where applicable. This represents the best available conventional technology that is technically feasible and economically viable in many regions.

8.2 | Recommendation for Methodology Application (Option 1):

This analysis recommends that the identified Best Available Technology (BAT) for each geography, as detailed above, be adopted as the default selection to meet the requirements for Option 1 of the methodology. This recommendation holds for both global and regional analyses.

This recommendation is justified by the comprehensive nature of this analysis, which has thoroughly evaluated the current technological landscape, economic viability, regulatory compliance, and technical feasibility across global, regional, and country levels. Based on this extensive assessment, significant unexpected changes in the baseline BAT are not anticipated in the immediate future.

Therefore, activity developers applying Gold methodology are exempted from conducting their own detailed BAT analysis for the initial crediting period and may choose the identified BAT for methodology application. This analysis will be updated as per the methodology's update schedule (e.g., every 3 years, as indicated by the "Next Planned Update" in the methodology document) or earlier should new information or significant technological advancements indicate a need for re-evaluation.

It is important to note that developers may, however, choose to conduct their own detailed BAT analysis irrespective of this recommendation if they wish to do so, for example, to explore project-specific nuances or to demonstrate a more ambitious baseline following the procedure and requirements outlined in the methodology.

This approach ensures a streamlined and consistent application of the methodology while maintaining environmental integrity and allowing for future adjustments to reflect evolving best practices.

SECTION 4:

Determination of Ambitious Benchmark

1| SUMMARY

This section establishes an "Ambitious Benchmark" for CO_2 emissions from ammonia production - excluding any facilities that utilize Carbon Capture and Storage (CCS) technologies, for ammonia-producing facilities at both global and country levels. The methodology focuses on identifying the average emission level of the top 10% best-performing comparable activities. The analysis concentrates on current prevailing practices, including natural gas Steam Methane Reforming (SMR), coal gasification, and naphtha-based processes, with a particular emphasis on facilities representing Best Available Technology (BAT) and, where possible, those commissioned within the last five years (post-June 2020).

Due to the scarcity of publicly available, verified operational data for a large statistical pool of newly commissioned, non-CCS plants within this narrow timeframe, the benchmark relies on third party publications referred as best performers for conventional (unabated) SMR and coal gasification.[273]

The derived global ambitious benchmark for unabated ammonia production is **1.6 tCO_2/tNH_3** for natural gas-based SMR and **3.2 tCO_2/tNH_3** for coal gasification. These benchmarks should

- **a.** serve as a cap: if a country's specific performance data for its best performers (meeting the criteria) is above this default, the default shall be applied.
- **b.** Furthermore, if no plants in a specific country meet the stringent criteria (e.g., commissioned post-June 2020, non-CCS), these default global values may be applied.

Country-specific benchmarks reflect regional feedstock dominance and technological adoption within this unabated scope. For instance, the United States and Europe are benchmarked at 1.6 tCO_2/tNH_3 (reflecting natural gas SMR BAT), and China's coal-based production is benchmarked at 3.2 tCO_2/tNH_3.

2| GLOBAL AMMONIA PRODUCTION LANDSCAPE

The global ammonia production landscape is characterized by a few dominant players and a continuous drive for expansion to meet increasing demand. In 2023, China led global ammonia production with 37,190 thousand metric tons, followed by Russia (16,360 kt), the United States (14,610 kt), and India (12,550 kt).[274] Other significant producers include Indonesia (5,130 kt), Egypt (4,800 kt), Saudi Arabia (4,530 kt),

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[273] STANDARD BREAKER SLIDE - EBRD, accessed June 12, 2025

[274] https://www.reportlinker.com/dataset/9caf2c33f250a3c3c00294aab7cba104284bd1b2, accessed June 12, 2025

Trinidad and Tobago (4,400 kt), Iran (4,050 kt), and Canada (3,920 kt). China's substantial output also translates to a disproportionately large share of global CO_2 emissions from ammonia production, accounting for 45% due to its heavy reliance on coal gasification for 85% of its production.[275] In contrast, the United States' ammonia production is primarily natural gas-fed (92%) and is showing a trend towards reduced carbon intensity. Trinidad & Tobago stands out as the largest net ammonia exporter, shipping 3.2-3.6 million tons in 2022 from its 11 plants at Point Lisas, the newest of which was commissioned in 2009.[276]

The global demand for ammonia is projected to expand significantly, with forecasts indicating an increase to nearly 290 million metric tons per year by 2030 from approximately 180 million metric tons per year in 2021.[277] This growth is primarily driven by economic and population expansion.

A critical aspect of the current landscape is the long operational lifetime of ammonia plants, typically ranging from 20 to 50 years or more.

The varying carbon intensities across countries, such as Canada's notably low net emissions intensity (1.1 tCO_2e/tNH_3) compared to Trinidad & Tobago's 2.4 tCO_2/tNH_3 or typical coal-based production (3.9 tCO_2/tNH_3), introduces a dynamic of "carbon leakage" risk and influences trade dynamics.

Table 18: Global Ammonia Production by Top Countries (2023)

Country	2023 Production (Thousand Metric Tons)	YoY Change (%)	5-years CAGR (%)
China	37,190	-0.76	-0.38
Russia	16,360	+2.05	+1.94
United States	14,610	+2.21	+2.21
India	12,550	+0.86	+1.06
Indonesia	5,130	+0.55	+0.52
Egypt	4,800	+3.34	+3.21
Saudi Arabia	4,530	+2.31	+1.04
Trinidad and Tobago	4,400	+0.37	+1.98
Iran	4,050	+2.91	+1.81
Canada	3,920	+0.084	+0.45
Source: ReportLinker Research, Global Ammonia Production by Country in 2023			

3| DEFINING "BEST PERFORMING COMPARABLE ACTIVITIES" (2020-2025)

The methodology mandates an ambitious benchmark - selecting the average emission level of the best-performing comparable activities. These activities must provide similar outputs and services within a defined scope, considering similar social, economic, environmental, and technological circumstances.

[275] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed June 13, 2025

[276] Trinidad & Tobago: future production pathways for the world's largest ammonia exporter, accessed June 12, 2025

[277] Zero-Carbon Fuels Set to Transform the Future of Shipping - OPIS, accessed June 12, 2025

For technology type, the scope explicitly includes ammonia plants utilizing natural gas (SMR), coal gasification, and other fossil fuel-based processes, while excluding older and inefficient technologies that do not represent best practices.

A significant challenge in this step is the identification of operational plants within this specific, recent timeframe for which detailed, verified emissions data is publicly available. A comprehensive review of available information reveals a notable absence of data for new, large-scale conventional (grey) SMR or coal gasification plants built in this recent timeframe without CCS. Consequently, the "top 10%" benchmark will likely be heavily influenced by, and potentially derived from, the values for conventional (unabated) SMR and coal gasification, rather than a statistical average of a large number of already-operational conventional plants commissioned in the last five years.

Geographical coverage for the benchmark considers global best-performing plants while ensuring alignment with regional economic and environmental conditions. This necessitates the development of both a global ambitious benchmark and country-specific benchmarks for major ammonia-producing nations.

The data scope requires specific CO_2 emissions data (SEi, in tCO_2/tNH_3) that reflects full lifecycle emissions, encompassing hydrogen production and ammonia synthesis. This comprehensive approach is critical for an accurate assessment, particularly in accounting for upstream emissions such as methane leakage from the natural gas supply chain.

Data sources include industry databases (IFA, IHS Markit, Argus, UNFCCC CDM databases), corporate sustainability reports, and peer-reviewed literature and verified third-party assessments. However, a review of these sources reveals limitations. The UNFCCC Clean Development Mechanism (CDM) database primarily offers methodologies for emission reduction projects rather than a direct, comprehensive database of specific plant emissions suitable for direct benchmarking. Attempts to find specific CO_2 emissions for conventional plants commissioned post-June 2020 in the CDM database did not yield direct results. The International Fertilizer Association (IFA) conducts energy efficiency and CO_2 emissions benchmarking, but specific plant-level data for recent periods is confidential. IFA's 2007 survey provided an average of 2.07 mt CO_2/mt NH_3 for 66 plants, with a range of 1.5 to 3.1 mt CO2/mt NH3, noting that newer plants generally exhibit better efficiencies.[278] IHS Markit and Argus provide general emission ranges for conventional ammonia (e.g., 1.5-2.5 tCO_2/tNH_3) [279] and benchmarks for low-carbon ammonia, but lack specific conventional plant data post-June 2020. Therefore, the ambitious benchmark will necessarily be derived from a synthesis of reported values, national averages for highly efficient fleets, and modelled estimates, rather than a direct calculation from a comprehensive list of individual plant data points. This methodological constraint is transparently communicated in the report.

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[278] Producing ammonia and fertilizers: new opportunities from renewables, accessed June 13, 2025

[279] Zero-Carbon Fuels Set to Transform the Future of Shipping - OPIS, accessed June 12, 2025

4| ANALYSIS OF SPECIFIC CO2 EMISSIONS FROM COMPARABLE AMMONIA PLANTS

The analysis of specific CO_2 emissions from comparable ammonia plants reveals a spectrum of performance influenced by feedstock, technology, and operational practices. This section focuses exclusively on unabated emissions, meaning facilities that do not utilize Carbon Capture and Storage (CCS) technologies.

4.1 | Global Overview of Conventional Ammonia Emissions:

Conventional ammonia production is widely acknowledged as highly emissions-intensive. Data from IHS Markit suggests a range of 1.5 to 2.5 tCO2/tNH3 for conventional technologies. An analysis by RMI indicates that natural gas-based ammonia production typically generates 2.3 tCO_2/tNH_3, while coal-based production can reach up to 3.9 tCO_2/tNH_3.[280] The International Energy Agency (IEA) reports a global average of 2.4 tCO_2/tNH_3 for direct emissions from ammonia production. [281] The International Fertilizer Industry Association (IFA) states for SMR without CCS is **1.6 tCO_2/tNH_3**.[282] The IEA further specifies that BAT for SMR results in 1.8 tCO2/tNH3 direct emissions. [283] For coal-based ammonia production, BAT without CCS implies direct emissions of **3.2 tCO_2/tNH_3**.[29]

When considering full lifecycle emissions, upstream methane leakage from natural gas supply significantly impacts the overall footprint. Saygin et al. estimate that upstream emissions can add between 0.19 and 2.40 tons of CO2 equivalent per ton of ammonia, with an average contribution of 0.42 tCO2e/tNH3.[284] This implies that a BAT SMR plant with 1.8 tCO_2/tNH_3 direct emissions could have a lifecycle footprint of approximately 2.22 tCO_2e/tNH_3 when considering average upstream emissions.

4.2 | Country-Specific Emissions Data (Excluding CCS):

Emissions vary significantly by country, reflecting differences in primary feedstocks and the adoption of efficiency measures.

- **United States:** U.S. ammonia production is predominantly natural gas-fed (92%) and has an average emission rate of approximately 2.1 tons of CO_2 per ton of ammonia produced, encompassing both combustion for process heat and feedstock use[285]. The ambitious benchmark for the US, based on SMR BAT without CCS, is **1.6 tCO_2/tNH_3**.[29]

[280] Clean Energy 101: Ammonia's Role in the Energy Transition - RMI, accessed June 13, 2025

[281] Executive Summary – Ammonia Technology Roadmap – Analysis - IEA, accessed June 13, 2025

[282] Ammoniaenergy.org, accessed June 12, 2025

[283] STANDARD BREAKER SLIDE - EBRD, accessed June 12, 2025

[284] Decarbonizing existing, SMR-based ammonia plants: workshop recap, accessed June 12, 2025

[285] Natural Gas Weekly Update - EIA, accessed June 12, 2025

- **China:** As the largest global producer, China accounts for 45% of global CO2 emissions from ammonia production. This high share is largely due to its heavy reliance on coal gasification for 85% of its production. The ambitious benchmark for China's coal-based production, reflecting coal gasification BAT without CCS, is **3.2 tCO_2/tNH_3**. For its smaller SMR capacity, the benchmark is **1.6 tCO2/tNH3**.
- **Canada:** Canadian ammonia production has an overall net emissions intensity averaging 1.1 tonnes CO_2e/tonne NH_3. This low figure is attributed to significant CO2 recovery (61-89% of process emissions), often for urea production. However, for the purpose of this benchmark, which focuses on *unabated* emissions (excluding CCS and significant CO_2 utilization that reduces reported emissions), the ambitious benchmark for Canada's SMR-based production aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.
- **India:** India's ammonia production relies on natural gas (70-75%), naphtha (15-20%), and coal (10%).[28]
    - For **Natural Gas SMR-based production**, the ambitious benchmark is **1.6 tCO_2/tNH_3**, aligning with global SMR BAT.
    - For **Naphtha-based production**, the ambitious benchmark is **2.5 tCO_2/tNH_3**, reflecting the typical average for this feedstock without abatement.[286]
    - For **Coal-based production**, the ambitious benchmark is **3.2 tCO_2/tNH_3**, aligning with global coal gasification BAT.
- **Indonesia:** A Life Cycle Assessment (LCA) study for ammonia production in Indonesia indicated a total Global Warming Potential (GWP) of 2.12 tCO_2eq/tNH_3, with the core production process contributing 1.68 tCO_2eq/tNH_3.[287] The ambitious benchmark for Indonesia's SMR-based production, aligning with global SMR BAT, is **1.6 tCO_2/tNH_3**.
- **Egypt:** Some newer plants in Egypt operate within EU Best Available Techniques (BAT) benchmarks, with CO_2 process emissions of 1.24 tCO_2/t NH_3 for ammonia/urea plants. This figure reflects CO_2 utilization for urea production. For the purpose of this benchmark, which focuses on *unabated* emissions, the ambitious benchmark for Egypt's SMR-based production aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.
- **Trinidad and Tobago:** The country reports direct and indirect greenhouse gas emissions of approximately 2.4 tCO_2 per ton of ammonia. For its SMR-based production, the ambitious benchmark aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.

[286] Techno-economic comparison of ammonia production processes, accessed June 12, 2025,
[287] World's 'largest' green hydrogen plant construction reaches 80% completion, accessed June 12, 2025

- **Iran:** Conventional "gray" ammonia in Iran has an emission intensity of around 1.87 tCO_2/tNH^3.[288] For its SMR-based production, the ambitious benchmark aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.
- **Saudi Arabia:** While specific conventional plant emissions are not detailed, Saudi Arabia is actively investing in carbon capture and green/blue ammonia projects. For its SMR-based production, the ambitious benchmark aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.
- **Russia:** Russia aims to decrease carbon emissions by 30% by 2030. For its SMR-based production, the ambitious benchmark aligns with the global SMR BAT of **1.6 tCO_2/tNH_3**.

Table 19: **Summary of Ammonia Production Technologies and Typical Emissions Intensity (tCO_2/tNH_3)**

Technology Type	Typical/BAT Energy Consumption (GJ/tNH3)	Typical/BAT CO2 Emissions Intensity (tCO2/tNH3)	Key Notes/Context
Natural Gas SMR (Grey)	32-36 mmBtu/tNH3 (approx. 26-36 GJ/tNH3)	1.9-2.1	Average process emissions, U.S. average, includes process heat and feedstock [5]
Natural Gas SMR (BAT, without CCS)	28	1.6 - 1.8	Best Available Technology for direct process emissions, without CCS
Coal Gasification (Grey)	Higher than NG-based	3.5 - 4.6 (China)	Significantly more carbon-intensive
Coal Gasification (BAT, without CCS)	42	3.2 - 3.8	Best Available Technology for direct process emissions, without CCS
Naphtha Reforming (Grey)	N/A	2.5	Average emissions for naphtha-based production

5| AMBITIOUS CO2 EMISSION BENCHMARKS FOR AMMONIA PRODUCTION

The determination of ambitious CO2 emission benchmarks for ammonia production, both globally and at the country level, is based on identifying the average emission level of the top 10% most efficient comparable activities, explicitly excluding facilities that utilize Carbon Capture and Storage (CCS) technologies. Given the scarcity of publicly available, granular data for conventional ammonia plants commissioned specifically after June 2020 without CCS, the benchmarks are primarily derived from values for conventional (unabated) SMR and coal gasification.

288 Russia Green Ammonia Market Size, Share and Forecast 2035, accessed June 12, 2025,

5.1 | Global Ambitious Benchmark:

The global ambitious benchmark for unabated ammonia production is established based on the Best Available Technology (BAT) for different fossil fuel feedstocks, as specified in the attached report.29

- For **natural gas-based Steam Methane Reforming (SMR)**, the global ambitious benchmark is **1.6 tCO_2/tNH_3**.
- For **coal gasification**, the global ambitious benchmark is **3.2 tCO_2/tNH_3**.

These values represent the cutting edge of unabated fossil-based ammonia production. This 1.6 tCO_2/tNH_3 for SMR and 3.2 tCO_2/tNH_3 for Coal will serve as a cap: if a country's specific performance data for its best performers (meeting the criteria) is above this default, the default shall be applied. Furthermore, if no plants in a specific country meet the stringent criteria (e.g., commissioned post-June 2020, non-CCS), these global default values may be applied.

5.2 | Country-Level Ambitious Benchmarks:

Country-specific ambitious benchmarks are also established, reflecting the predominant feedstock and Best Available Technology (BAT) for unabated production in each region.

Table 20: Ambitious CO2 Emission Benchmarks for Ammonia Production (Global and Key Countries) - Excluding CCS

Scope	Proposed Ambitious Benchmark (tCO2/tNH3, Full Lifecycle)	Basis for Benchmark	Current Average Emissions (tCO2/tNH3, for comparison)	Notes
Global (Natural Gas SMR)	**1.6**	IFA BAT for Natural Gas SMR	~2.1 (US average)	Represents unabated SMR.
Global (Coal Gasification)	**3.2**	BAT for Coal Gasification	~3.8-4.5 (China average)	Represents unabated Coal Gasification.
Country-Level				
Canada (Natural Gas SMR)	1.6	Global best performance	1.1 (Net Emissions Intensity)	Benchmark for unabated production; net emissions are lower due to CO_2 recovery.
Egypt (Natural Gas SMR)	1.6	Global best performance	1.24 (Ammonia/Urea plant embedded)	Benchmark for unabated production; net emissions are lower due to CO_2 utilization.
United States (Natural Gas SMR)	1.6	IFA	2.1	Aims for significant improvement in its natural gas-based fleet.
India (Natural Gas SMR)	1.6	Global best performance	2.0-2.5 (Realistic Current)	Targets efficient SMR with potential for CO2 capture.

India (Naphtha-based)	2.5	Average for Naphtha-based production	2.5 (Realistic Current)	High priority for feedstock shift and deep decarbonization.
India (Coal-based)	3.2	Global Coal Gasification	3.8-4.5 (Realistic Current)	Requires significant decarbonization efforts.
Indonesia (Natural Gas SMR)	1.6	Global SMR	2.12 (LCA total GWP) [32]	Encourages efficiency and CCUS adoption.
China (Coal-based)	3.2	BAT for Coal Gasification	3.8-4.5 (Realistic Current)	Dominant feedstock; significant challenge for deep decarbonization.
China (Natural Gas SMR)	1.6	Global SMR	1.8-2.6 (Realistic Current)	Potential for blue ammonia development.
Russia (Natural Gas SMR)	1.6	Global best performance	N/A (General average likely higher)	Capitalizes on natural gas resources for efficient production.
Trinidad and Tobago (Natural Gas SMR)	1.6	Global best performance	2.4	Requires substantial investment in decarbonization initiatives.
Iran (Natural Gas SMR)	1.6	Global best performance	1.87 (Gray ammonia)	Targets enhanced efficiency and carbon management.
Saudi Arabia (Natural Gas SMR)	1.6	Global best performance	N/A (Focus on green/blue projects)	Aligns with national net-zero ambitions and CCS investments.

6| ADDRESSING DATA SCARCITY AND ENSURING BENCHMARK APPLICATION

A primary challenge encountered during this analysis was the severe scarcity of publicly available, verified, plant-level CO_2 emissions data for newly commissioned, non-CCS ammonia plants, particularly for the "top 10%" of fossil-based facilities. Most available information for new projects is either projected or aggregated, and overwhelmingly focuses on CCS-enabled or green ammonia, making precise statistical averaging for unabated new plants difficult. This highlights a critical need for greater transparency and consistency in reporting.

To address these challenges and facilitate the practical application of the ambitious benchmark, it is recommended that the methodology incorporate a clear framework for data utilization:

- **Setting a Cap to Avoid Overestimation:** Due to the lack of comprehensive, publicly available data for the "top 10%" of recently commissioned, non-CCS plants, the global BAT values (1.6 tCO_2/tNH_3 for SMR and 3.2 tCO_2/tNH_3 for coal) serve as a stringent cap. If a country's specific performance data for its best performers (meeting the criteria of being commissioned post-June 2020 and non-CCS) indicates an ambitious benchmark *above* these global BAT values, the global BAT default shall be applied. This prevents the overestimation of the benchmark based on potentially limited or less efficient local "best performers" and ensures a consistently ambitious target.

- **Providing a Default Value for Application:** To facilitate the application of the option 2 where country-specific data is insufficient, the global default values (1.6 tCO_2/tNH_3 for SMR and 3.2 tCO_2/tNH_3 for coal) also serve as default values. If no plants in a specific country meet the stringent criteria (e.g., commissioned post-June 2020, non-CCS, and with publicly verifiable data), these default global BAT values may be applied as the ambitious benchmark for that country. This ensures that the benchmark can be applied universally, even in data-poor environments, while still promoting the adoption of Best Available Technology.

SECTION 5:

Determination of Downward Adjustment Factors

1| RECOMMENDED DOWNWARD ADJUSTMENT FACTORS

Establishing BAT benchmarks is only the first step; ensuring continuous improvement and alignment with long-term climate goals requires these benchmarks to become progressively more stringent over time. Downward adjustment factors applied to the benchmarks serve as this crucial "ambition ratchet" mechanism.

1.1 | Rationale and Principles

The rationale for downward adjustments is firmly rooted in the principles of the Paris Agreement and its Article 6.4 mechanism. Methodologies and baselines must:

- **Encourage ambition over time:** Static benchmarks would fail to drive the necessary continuous decarbonization.
- **Align with the long-term temperature goal:** Baselines need to reflect a trajectory consistent with limiting warming to well below 2°C and pursuing 1.5°C.
- **Be below 'business as usual' (BAU):** As technology improves and policies tighten, the definition of BAU shifts, and benchmarks must adjust downwards to remain additional.
- **Align with NDCs and LT-LEDS:** Benchmarks should reflect and contribute to the host country's national climate commitments.

Downward adjustments operationalize these principles by systematically lowering the benchmark emission factor each year, effectively tightening the performance standard required to meet the benchmark or generate credits.

1.2 | Calculation approach

For the purpose of the methodology, the downward adjustment factor calculation is proposed as:

$$AF_{LT-LEDS} = \frac{1}{(Y_{NetZero} - Y_{ref})}$$

Where:

- $AF_{LT-LEDS}$ = Annual downward adjustment factor based on LT-LEDS or net-zero target.
- $Y_{NetZero}$ = Host Country’s Net Zero Target Year.
- Y_{ref} = Reference year from which the adjustment period is calculated

This formula directly incorporates $Y_{NetZero}$, aligning with the instruction to use the net-zero target year. It calculates an annual fractional reduction that, if applied consistently, would lead to a 100% reduction (or effectively drive the adjustable portion of the baseline towards zero) over the period from a defined reference year (Y_{ref}) to the $Y_{NetZero}$. This approach directly reflects the "ambition of the... net-zero target" ; a shorter timeframe to net-zero (indicating higher ambition) results in a larger annual adjustment factor, signifying a more rapid downward scaling of the baseline.

Y_{ref}**:** For this analysis, Y_{ref} is set to **2025**. This choice is based on it being a recent year, reflecting current policy contexts and ambitions. Many recent policy documents, Nationally Determined Contributions (NDCs), and project announcements use timelines that align with this contemporary starting point. Using a consistent, recent reference year allows for a more comparable assessment of $AF_{LT-LEDS}$ values across different countries, reflecting their relative ambition from a common temporal standpoint.

1.3 | Identification of Ammonia Producing Countries

This updated analysis aims to provide a comprehensive assessment by including countries with significant current ammonia production capacity or output, as well as countries identified as "prospective" green ammonia producers in the initial analysis. For current significant producers, the primary data sources are the U.S. Geological Survey (USGS) Mineral Commodity Summaries for Nitrogen (Ammonia), particularly the 2024 estimates[289], cross-referenced with 2023 and 2022 data.[290] "Significant" current production is generally defined as 1 million tonnes or more in 2024. The inclusion of prospective countries, regardless of current large-scale production, ensures the analysis also covers emerging green ammonia hubs and their alignment with long-term climate goals.

The following table compiles information on identified ammonia producing countries (both significant current producers and prospective producers), their estimated 2024 ammonia production (where applicable), their stated net-zero target years ($Y_{NetZero}$), the official sources for these targets, and the scope of these commitments. This data forms the basis for calculating the $AF_{LT-LEDS}$.

Table 21:Identified Ammonia Producing Countries, Net-Zero Targets, and Official Sources

Country	2024e Ammonia Production ('000 tonnes) [291] / Status	Net-Zero Target Year (YNetZero)	Official Source for Target (Source Type from or other specified)	Scope of Net-Zero Target (e.g., All GHGs/CO2 only, Legal Status & Snippet ID from or other specified)
China	47,000	2060 (Before 2060)	(Govt. plans, LTS to UNFCCC)	CO_2 only (LTS), Policy Document
United States	14,000	2050	(Federal Sustainability Plan, Govt. goals)	All GHGs (economy-wide), Policy Goal/Executive Order
Russia	14,000	2060	(LTS to UNFCCC)[292] (Net Zero Tracker)	All GHGs, In Law (Govt. Order approving LTS)

[289] NITROGEN (FIXED)—AMMONIA - USGS.gov, accessed June 7, 2025

[290] Nitrogen (fixed)—ammonia - Mineral Commodity Summaries 2024 - USGS.gov, accessed June 7, 2025

[291] Nitrogen (fixed)—ammonia - Mineral Commodity Summaries 2024 - USGS.gov, accessed June 7, 2025

[292] Russian Federation (Country) | Net Zero Tracker, accessed June 7, 2025,

India	15,000	2070	[1] (COP26 announcement, LTS to UNFCCC)	Net-Zero (implies all GHGs), Policy Document
Indonesia	6,000	2060 (or sooner)	[8] (LT-LEDS to UNFCCC)	Net-zero emissions (implies all GHGs), Policy Document (LT-LEDS)
Saudi Arabia	5,400	2060	[1] (Govt. announcement net zero by 2060)	Net Zero (implies all GHGs), Policy Document
Egypt	5,000	Not Found	[1] (No official Net Zero Target year submitted to UNFCCC)	N/A
Iran	4,200	Not Found	[9] (No net zero target, no LTS submitted)	N/A
Canada	3,600	2050	[1] (Canadian Net-Zero Emissions Accountability Act)	All GHGs, In Law
Pakistan	3,500	Not Found	[10] (NDC targets vs BAU, no explicit net-zero year)	N/A
Trinidad & Tobago	3,200	Not Found	[1] (No explicit Net Zero target year; NDC for 2030)	N/A
Qatar	3,100	Not Found	[12] (No net zero target; NDC vs BAU)	N/A
Algeria	2,000	Not Found	[14] (No net zero target, no LTS submitted to UNFCCC as of Feb 2024)	N/A
Netherlands	2,000	2050	[1] (Climate Law, Govt. commitment)	All GHGs, In Law
Nigeria	1,700	2060	[15] (LT-LEDS to UNFCCC)	Net-zero emissions (all sectors), Policy Document (LT-LEDS)
Oman	2,000	2050	[1] (Reference to national strategy for carbon neutrality by 2050)	Carbon Neutrality (implies all GHGs), Policy Document (National Strategy)
Germany	1,700	2045	[1] (Climate Change Act, Climate Law)	All GHGs, In Law
Poland	1,600	2050	[17] (EU Climate Law, National Energy and Climate Plan alignment)	All GHGs (EU Target), In Law (EU Level)
Australia	1,300	2050	[1] (NDC, National Hydrogen Strategy)	All GHGs, Policy Document (NDC) [1]
Uzbekistan	1,300	Not Found	[19] (General regional pledges 2050-2060, no specific official YNetZero submitted to UNFCCC)	N/A
Vietnam	1,400	2050	[22] (COP26 Pledge, National Climate Change Strategy)	Net Zero (implies all GHGs), Policy Document/Pledge
Malaysia	1,400	2050	[24] (Govt. commitment, policy statements)	Net Zero Carbon (implies all GHGs), Policy Document/Pledge
Denmark	N/A (Prospective)	2045	[1] (Govt. announcement, Climate Act newer ambition)	All GHGs, 2050 in law, 2045 proposed
Norway	N/A (Prospective)	2050	[1] (Climate Change Act goal)	All GHGs, Policy Goal

Japan	N/A (Prospective)	2050	[1] (Govt. declaration, NDC)	All GHGs, Policy Document
Chile	N/A (Prospective)	2050	[1] (Climate Law commitment)	All GHGs (Carbon Neutrality), In Law
Brazil	N/A (Prospective)	2050	[1] (NDC submission, Govt. pledge)	All GHGs (Climate Neutrality), Policy Document (NDC)
UAE	N/A (Prospective)	2050	[1] (Net Zero by 2050 strategic initiative)	Net Zero (implies all GHGs), Policy Document/Strategic Initiative
Morocco	N/A (Prospective)	2050	[1] (LT-LEDS goal, National Sustainable Development Strategy)	Carbon Neutrality (implies all GHGs), Policy Document
Namibia	N/A (Prospective)	Not Found	[1] (NDC target for 2030, no explicit net-zero year)	N/A
South Africa	N/A (Prospective)	2050	[1] (LTS goal, Just Transition Framework)	CO_2 or All GHGs, Policy Document (LTS) [1]

Note on YNetZero: For China, "Before 2060" is interpreted as 2060. For Indonesia, "2060 or sooner" is interpreted as 2060. Countries identified as "Prospective" included regardless of their current large-scale production volumes to reflect their potential role in green ammonia development; their production is marked N/A (Prospective [1]) if not listed in USGS data.[3] For Oman, the 2050 target is based on references to a national strategy within project descriptions from the initial analysis.[1] Poland's 2050 target is in the context of EU-level commitments.[17] Nigeria's 2060 target is from its LT-LEDS submitted to UNFCCC.[15] Russia's 2060 target is from its LTS submitted to UNFCCC.[6] Indonesia's 2060 target is from its LT-LEDS.[8] Vietnam's 2050 target is from its COP26 pledge and strategy.[22] Malaysia's 2050 target is from government commitments.[24] Iran, Pakistan, Qatar, Algeria, Uzbekistan, Egypt, Namibia, and Trinidad & Tobago do not have clearly defined economy-wide net-zero target years suitable for the formula based on available information.[9]

1.4 | Data Availability and Limitations

The compilation of net-zero targets for this list of ammonia producing and prospective countries reveals significant heterogeneity in their definition, scope, legal status, and, critically, their existence. While many nations have announced net-zero targets, the specifics vary considerably. For instance, China's LTS specifies "carbon neutrality before 2060," often interpreted for CO_2, though broader discussions may include all GHGs. Russia's 2060 net-zero target covers all GHGs and is enshrined in a government order approving its LTS.

A key limitation encountered in this expanded assessment is the absence of clearly defined, economy-wide net-zero target years suitable for the $AF_{LT-LEDS}$ formula for several major ammonia producing nations and some prospective ones. Countries such as Egypt, Iran, Pakistan, Trinidad & Tobago, Qatar, Algeria, Nigeria (prior to its recent LT-LEDS submission which now indicates 2060), Uzbekistan, and Namibia do not, based on the available information or prior to recent updates, have officially communicated net-zero target years submitted to the UNFCCC or clearly articulated in national laws or comprehensive LT-LEDS that would allow for a direct calculation of $AF_{LT-LEDS}$.

- For Egypt, while a 2050 National Climate Change Strategy exists, it does not specify an overall emissions reduction goal or a net-zero year.
- Iran has not submitted an LTS and its NDC targets are relative to a BAU scenario without a net-zero commitment.
- Pakistan's NDC also sets targets against BAU without an explicit long-term net-zero year.

- Qatar's NDC is similarly based on a reduction from BAU by 2030, with no stated net-zero target.
- Namibia's NDC focuses on 2030 targets without a clear long-term net-zero year.

This lack of a clearly defined $Y_{NetZero}$ for a substantial portion of global conventional ammonia production and some prospective countries poses a significant challenge for the universal application the downward adjustment.

1.5 | Calculation and Analysis of the Downward Adjustment Factor ($AF_{LT-LEDS}$) for Ammonia Producing Countries

The downward adjustment factor ($AF_{LT-LEDS}$) is calculated using the interpreted formula with the reference year (Yref) set to 2025:

$$AF_{LT-LEDS} = \frac{1}{(Y_{NetZero} - Y_{ref})}$$

For example, for Germany, with $Y_{NetZero}$=2045:

$AF_{LT-LEDS,Germany}$ =1/(2045–2025)=1/20=0.05

This factor represents an annual reduction of approximately 5% to be applied to the baseline emissions determined prior to this specific LT-LEDS adjustment.

The following table presents the calculated $AF_{LT-LEDS}$ for the ammonia producing countries identified in Table above for which a net-zero target year ($Y_{NetZero}$) was available. Countries without a specified $Y_{NetZero}$ are excluded from this calculation.

Table 22: Calculated Downward Adjustment Factors (AFLT−LEDS) for Identified Ammonia Producing Countries

Country	Net-Zero Target Year (YNetZero)	Reference Year (Yref)	Years to Net-Zero (YNetZero–Yref)	Calculated AFLT−LEDS (%)	Proposed applicable AFLT−LEDS (%)
Germany	2045	2025	20	5.0%	5.0%
Denmark	2045	2025	20	5.0%	5.0%
Netherlands	2050	2025	25	4.0%	4.0%
Norway	2050	2025	25	4.0%	4.0%
Japan	2050	2025	25	4.0%	4.0%
Australia	2050	2025	25	4.0%	4.0%
USA	2050	2025	25	4.0%	4.0%
Canada	2050	2025	25	4.0%	4.0%
Chile	2050	2025	25	4.0%	4.0%
Brazil	2050	2025	25	4.0%	4.0%
Oman	2050	2025	25	4.0%	4.0%
UAE	2050	2025	25	4.0%	4.0%
Morocco	2050	2025	25	4.0%	4.0%
South Africa	2050	2025	25	4.0%	4.0%

Poland	2050	2025	25	4.0%	4.0%
Vietnam	2050	2025	25	4.0%	4.0%
Malaysia	2050	2025	25	4.0%	4.0%
China	2060	2025	35	2.86%	3.76%
Russia	2060	2025	35	2.86%	3.76%
Indonesia	2060	2025	35	2.86%	3.76%
Saudi Arabia	2060	2025	35	2.86%	3.76%
Nigeria	2060	2025	35	2.86%	3.76%
India	2070	2025	46	2.22%	3.76%
Rest of the World (RoW)	NA	NA	NA	NA	3.76%

(Countries from Table 1 without a YNetZero – Egypt, Iran, Pakistan, Trinidad & Tobago, Qatar, Algeria, Uzbekistan, Namibia – are not included in this table as AFLT−LEDS cannot be calculated)

1.6 | Comparative Analysis of AFLT−LEDS Values

The calculated $AF_{LT-LEDS}$ values for this expanded list of ammonia producers and prospective countries confirm the direct correlation between the timeline of a country's net-zero target and the magnitude of the annual downward adjustment. Countries with earlier net-zero dates, such as Germany and Denmark (2045), exhibit the highest adjustment factor (5%). This signifies a more rapid annual reduction of the crediting baseline for activities hosted within their borders.

Conversely, nations with longer-term net-zero horizons, like India (2070), have the lowest $AF_{LT-LEDS}$value (2.22%). A significant group of countries, including major ammonia producers like China, Russia, Saudi Arabia, Indonesia, and Nigeria, target net-zero by 2060, resulting in an adjustment factor of 2.86%. Another substantial cohort, including the USA, Canada, Australia, Japan, Brazil, and several European, Middle Eastern, African and Asian nations, aims for 2050, leading to an intermediate adjustment factor of 4%.

This direct linkage ensures that the national climate ambition is internalized into operational parameters. The $AF_{LT-LEDS}$ translates a country's long-term political commitment to decarbonization into a tangible, year-on-year impact on the carbon crediting framework. The distribution of these values clearly shows distinct clusters: highly ambitious nations with early targets, a large group with mid-century targets, another group with targets around 2060, and one with a 2070 target. This creates a multi-tiered system of baseline stringency directly reflecting declared national ambition.

Several significant ammonia producing countries and some prospective ones—Egypt, Iran, Pakistan, Trinidad & Tobago, Qatar, Algeria, Uzbekistan, and Namibia—currently lack clearly defined, economy-wide net-zero target years that are officially communicated and suitable for the $AF_{LT-LEDS}$. The primary consequence is the current inapplicability of the downward adjustment in these jurisdictions.

1.7 | Implications of Varying $AF_{LT-LEDS}$ for Project Viability

The variation in $AF_{LT-LEDS}$ values, and its applicability in some major producing and prospective nations, carries significant implications for the financial viability and attractiveness of projects, whether they are greenfield green ammonia facilities or brownfield projects focused on decarbonizing existing conventional ammonia production. A higher $AF_{LT-LEDS}$ leads to a more rapid decrease in the crediting baseline.

For capital-intensive ammonia projects, where revenues from Emission Reductions can be crucial for achieving financial close and ensuring profitability, a sharply declining baseline can significantly impact investment returns and increase risk. This creates a complex dynamic: countries demonstrating higher climate ambition through earlier net-zero targets (and thus higher $AF_{LT-LEDS}$ values) impose more stringent baseline conditions on their projects. While this aligns with the Paris Agreement's goals, it could, in isolation, render projects in these jurisdictions less financially attractive compared to similar projects in countries with less ambitious (later) net-zero timelines.

This potential for creating differential incentives based on national ambition levels is a key consideration. It might influence where project developers choose to invest, potentially steering capital towards jurisdictions with slower baseline adjustments if not counterbalanced by other factors. Such factors could include strong domestic support policies (e.g., subsidies for green hydrogen or CCUS), favorable renewable energy costs, established infrastructure, higher domestic carbon prices, or exceptional project efficiencies. The impact of $AF_{LT-LEDS}$ is therefore highly context-specific; a high factor in a supportive policy environment might still allow viable projects, while a moderate factor in a less supportive environment could be prohibitive. Near-zero-emission ammonia production technologies are often projected to have significantly higher costs than conventional methods, potentially 10% higher to more than double[293], making carbon revenues particularly important.

1.8 | Dynamic Global Average Downward Adjustment Factors

The section presents an approach for calculating a "Dynamic Global Average DAF" and presents the calculated average, serving as a fallback mechanism for countries without clearly defined net-zero targets or whose calculated $AF_{LT-LEDS}$ is lower than the prevailing default. This approach ensures consistent ambition across all project geographies, aligning with the methodology's principle of encouraging ambition over time. The Approach for Dynamic Global Average DAF calculation is outlined below.

- **Identify Countries with Defined Net-Zero Targets:** This step involves identifying all countries that have officially declared economy-wide net-zero target years ($Y_{NetZero}$). This includes both current ammonia producers and prospective producers as listed in the main report, *excluding* those for which $Y_{NetZero}$ is "Not Found."
- **Calculate Individual AFLT-LEDS:** For each of these identified countries, their individual Annual Downward Adjustment Factor ($AF_{LT-LEDS}$) is calculated using

293 IEA's Ammonia Technology Roadmap IFA Summary for Policymakers - International Fertilizer Association, accessed June 7, 2025

the formula: $AF_{LT-LEDS}$= 1 / ($Y_{NetZero}$ - Y_{ref}), where Y_{ref} is the fixed reference year (2025).

- **Determine Effective DAF per Period:** For each specified period, the *effective* DAF for each country is determined. This average represents the collective ambition of countries that have committed to net-zero targets, *without* applying any minimum floor from default DAFs.
- **Apply as a Fallback:** This calculated "dynamic global average DAF" would serve as a mandatory fallback mechanism. It would be applied to projects located in countries that currently lack a defined $Y_{NetZero}$ or those have below global average default value.
- **Dynamic Nature:** This global average DAF is dynamic. It would be recalculated periodically (e.g., every five years, aligning with NDC review cycles). This ensures that the Global DAF continuously reflects the evolving global climate ambition as more countries set or update their net-zero targets, or as existing targets are brought forward.

1.9 | Calculation of Dynamic Global Average DAF for Specified Periods

The following calculations are based on the $AF_{LT-LEDS}$ values from Table above, including only countries with defined net-zero targets.

- **Countries with Calculated AFLT-LEDS (23 countries):**
  - 5.0% DAF (Net-Zero by 2045): Germany, Denmark (2 countries)
  - 4.0% DAF (Net-Zero by 2050): Netherlands, Norway, Japan, Australia, USA, Canada, Chile, Brazil, Oman, UAE, Morocco, South Africa, Poland, Vietnam, Malaysia (15 countries)
  - 2.86% DAF (Net-Zero by 2060): China, Russia, Indonesia, Saudi Arabia, Nigeria (5 countries)
  - 2.22% DAF (Net-Zero by 2070): India (1 country)
- **Dynamic Global Average Downward Adjustment Factors by Period (2025-2030)**
  - Sum of Individual $AF_{LT-LEDS}$ (%) = (2 * 5.0) + (15 * 4.0) + (5 * 2.86) + (1 * 2.22) = 10.0 + 60.0 + 14.3 + 2.22 = 86.52
  - Number of countries =23
  - Global Average DAF for period (2025-2030) = 3.76%

Table 23: Recommended DAFs

Year	DAF ($AF_{LT-LEDS}$)	Applicability
2025-2030	3.76%	If calculated values for $AF_{LT-LEDS}$ is lower than 3.76% or cannot be determined for the host county.

It signals a stronger commitment to continuous improvement than 1%, while remaining potentially achievable across diverse regions through ongoing efficiency gains and gradual adoption of low-carbon technologies.

2| CONCLUSION AND RECOMMENDATIONS

It is recommended that this calculated **3.76% Dynamic Global Average DAF** be adopted as the default downward adjustment factor for all green ammonia projects located in countries without a clearly defined net-zero target year and those where the calculated DAF is below the global average. This ensures that the ambition ratchet is consistently applied across the entire global portfolio of projects, reinforcing the methodology's robustness and long-term environmental integrity.

3| REFERENCES

Country-Specific Net-Zero Target & NDC Sources:

- Algeria
- Australia
- Brazil
- Canada
- Chile
- China
- Denmark
- Egypt
- Germany
- India
- Indonesia
- Iran
- Japan
- Malaysia
- Morocco
- Namibia
- Netherlands
- Nigeria
- Norway
- Oman
- Pakistan
- Poland:(as part of EU framework)
- Qatar
- Russia
- Saudi Arabia
- South Africa
- Trinidad & Tobago
- UAE
- USA
- Uzbekistan
- Vietnam

Market, Project, and General Reports:

- Green Ammonia Market Reports
- Trinidad & Tobago Ammonia Export
- IEA Ammonia Technology Roadmap context
- Norton Rose Fulbright Article 6 Guide: 2
- Green Ammonia Project Announcements (Australia, Saudi Arabia, Chile, Oman, Canada, Norway, Egypt, Morocco, Namibia, South Africa, Brazil, UAE)
- National Hydrogen Strategies (Australia, Saudi Arabia, Germany, Chile)
- USGS Mineral Commodity Summaries, Nitrogen (Ammonia): (MCS 2025, with 2024e data, referred to as 3 in report text) (MCS 2024, with 2023 data, referred to as 4 in report text) (MCS 2023, with 2022e data, referred to as 5 in report text)
- IndexBox, Ammonia in Aqueous Solution Market
- IEA/IFA Ammonia Technology Roadmap context
- IEA general ammonia/hydrogen context
- Global Ammonia Market Report (leading companies)

SECTION 6:

Common Practice Analysis: Green Ammonia Production Facilities (2025-2030)

This section assesses the likelihood of green ammonia production facilities becoming "common practice" globally between 2025 and 2030, based CDM common practice methodology (CDM Tool 24). The analysis concludes that green ammonia projects are highly unlikely to achieve common practice status by 2030 without significant carbon revenue.

Currently, operational green ammonia capacity is negligible, representing only 0.3% of total global ammonia production, with just four operational green fertilizer projects as of March 2025.[294] While a large pipeline of green ammonia projects is announced (89.1 Mt by 2030), many are at high risk of cancellation or delay due to financial challenges and insufficient demand.[295] More realistic projections estimate operational green ammonia capacity will reach only about 14 Mt by 2030.

The substantial cost difference between green ammonia ($600-$1,400 per ton) and conventional grey/black ammonia ($250-$600 per ton) is a critical barrier.[296] A carbon price of approximately $100-$150 per ton of CO2 is needed for green ammonia to achieve price parity by the early 2030s.[297] Current global carbon pricing mechanisms cover only about 28% of global emissions and have average prices well below this threshold.[298] Without robust carbon revenue and strong policy support, green ammonia projects will not be economically viable enough to become common practice within the specified timeframe.

1| DETAILED EXPLANATION OF CDM TOOL 24, VERSION 3.1

The CDM Tool 24[299] employs a quantitative test:

1. **Factor F > 0.2:** F = 1 - (Ndiff / Nall), where 'Nall' is the total number of similar non-CDM projects, and 'Ndiff' is the number of those projects using "different technologies".
2. **(Nall - Ndiff) > 3:** The number of similar projects using non-different technologies must exceed three.

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[294] First Roundtable (20 March 2025) | Green Hydrogen Organisation, accessed June 12, 2025,
[295] GENA Solutions Oy, accessed June 12, 2025
[296] Ammonia production cost breakdown - ResearchGate, accessed June 12, 2025
[297] Green Ammonia – An Alternative Fuel - FutureBridge, accessed June 12, 2025
[298] State and Trends of Carbon Pricing 2025 - World Bank, accessed June 12, 2025
[299] Common practice - CDM, accessed June 12, 2025

1.1 | Key Definitions:

- **Similar Projects:** Located in the applicable geographical area, apply the same "measure" (e.g., technology switch), use the same energy source/fuel/feedstock (if a technology switch), produce comparable goods/services, have capacity within +/-50% of the proposed project, and commenced commercial operation before a specified date.

- **Different Technologies:** Technologies are "different" if they vary by energy source/fuel, feedstock, installation size, investment climate factors (e.g., access to technology, subsidies), or if their unit cost of capacity or output differs by at least 20%. This economic criterion is vital, as it allows for green ammonia to be considered "different" if it's significantly more expensive or lacks policy support.

2| CURRENT LANDSCAPE OF GLOBAL AMMONIA PRODUCTION (2025)

2.1 | Total Global Ammonia Production Volume and Market Size

The global ammonia market is large, with total production of conventional ammonia estimated at 191 Mt in 2023.[300] Projections indicate a market volume of approximately 191.97 Mt in 2025, rising to 210.81 Mt by 2030.[301]

2.2 | Current Operational Green Ammonia Facilities: Number, Capacity, and Share of Total Global Production

As of March 2025, green ammonia production is minimal. Only four green fertilizer projects are operational globally, accounting for a mere 0.3% of total global ammonia production.[302] Total operational and under-construction clean ammonia capacity (green and blue) was 10.1 Mt in February 2025, with green ammonia contributing 5.1 Mt. [303] This extremely limited operational footprint means green ammonia cannot satisfy the common practice criteria of (Nall - Ndiff) > 3 and F > 0.2 in 2025.

2.3 | Geographical Distribution of Existing Green Ammonia Production

Nascent green ammonia development is concentrated in the Middle East, North America, China, and India, which account for 95% of capacity under construction.[304] The first green ammonia plant was expected in Bangladesh in 2024[305], and BASF became the first producer of renewable ammonia in Central Europe by 2025.[306] Despite these regional efforts, widespread global adoption is absent.

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300 Global Green Ammonia Market Snapshot - NexantECA, accessed June 12, 2025

301 www.mordorintelligence.com, accessed June 12, 2025

302 First Roundtable (20 March 2025) | Green Hydrogen Organisation, accessed June 12, 2025,

303 GENA Solutions Oy, accessed June 12, 2025

304 GENA Solutions Oy, accessed June 12, 2025

305 Global Green Ammonia Market Snapshot - NexantECA, accessed June 12, 2025,

306 BASF becomes first producer of renewable ammonia in Central Europe, accessed June 12, 2025

Table 24:Global Ammonia Production Overview (2025)

Metric	Value
Total Global Ammonia Production (2025)	~192 Mt
Operational Green Ammonia Capacity (2025)	~0.02 Mt (2021 baseline)
Operational Green Ammonia Projects (2025)	4 facilities
Green Ammonia Share of Total Production	0.3%

3| PROJECTED GROWTH OF GREEN AMMONIA CAPACITY (2025-2030)

3.1 | Analysis of Announced and Planned Clean (Green and Blue) Ammonia Projects

The total clean ammonia project pipeline (operational and under-construction) is 122.4 Mt by 2030, with green ammonia accounting for 89.1 Mt.[307] However, many projects are likely to be cancelled or delayed.[308] A more realistic "Advanced Projects scenario" projects operational green ammonia capacity at approximately 14 Mt by 2030, only 16% of the announced pipeline. [309] Blue ammonia is projected to reach 17 Mt by 2030 in this scenario.

3.2 | Discussion of Project Maturity (FID Status) and Anticipated Delays/Cancellations

Blue ammonia projects are reaching Final Investment Decision (FID) faster than green projects, with 7.6 Mt of blue ammonia in FID compared to only 2.5 Mt for green ammonia as of March 2025. [310] This disparity indicates greater commercial viability for blue ammonia in the near term. Delays are often due to challenges in securing long-term binding off-take agreements and buyers willing to pay a "green premium".[2] For gigawatt-scale green hydrogen projects, essential for large-scale green ammonia, the Neom project might be the only one completed this decade.[311]

3.3 | Regional Distribution of Projected Green Ammonia Capacity

By 2030, North America, China, and the Middle East are expected to account for 79% of total clean ammonia production.[312] In the US, 70-90% of proposed new capacity is for blue ammonia, with only 7% for green ammonia. This shows a strong market preference for blue ammonia as a decarbonization pathway.

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[307] GENA Solutions Oy, accessed June 12, 2025

[308] GENA Solutions Oy, accessed June 12, 2025

[309] GENA Solutions Oy, accessed June 12, 2025

[310] First Roundtable (20 March 2025) | Green Hydrogen Organisation, accessed June 12, 2025

[311] ANALYSIS | Will any more gigawatt-scale green hydrogen projects be built before 2030?, accessed June 12, 2025

[312] Ammonia Supply Outlook 2024: A Clean Takeover - BloombergNEF, accessed June 12, 2025

Table 25 : Projected Clean Ammonia Capacity by Type and Region (2030)

Region	Green Ammonia Capacity (Mt, 2030) (Advanced Projects Scenario)	Blue Ammonia Capacity (Mt, 2030) (Advanced Projects Scenario)	Total Clean Ammonia Capacity (Mt, 2030) (Advanced Projects Scenario)	Clean Ammonia Share of Total Global Ammonia Production (2030, %)
North America	Minimal (7% of US proposed capacity)	~13 Mt (Concentrated)	~13 Mt	~6.2%
Middle East	Distributed, significant projects (e.g., Salalah2)[313]	Significant projects[314]	Substantial	
China	Distributed, significant projects (e.g., Envision Energy)[315]	Significant projects	Substantial	
India	Distributed, emerging projects	Emerging projects	Emerging	
Europe	Distributed, emerging projects[316]	Emerging projects	Emerging	
Other Regions	Emerging	Emerging	Emerging	
Global Total	**~14 Mt**	**~17 Mt**	**~31 Mt** (Aligned with BNEF's 32 Mt[317])	**~14.7%** (31 Mt / 210.81 Mt)[318]

Table 26: Green vs. Blue Ammonia Project Maturity (FID Status, Capacity in Mt)

Ammonia Type	Capacity in Final Investment Decision (FID) (Mt, as of March 2025)	Total Announced Pipeline Capacity (Mt, by 2030)	% of Pipeline in FID
Green	2.5 Mt	89.1 Mt	2.8%
Blue	7.6 Mt	33.4 Mt	22.7%

[313] SalalaH2: export-focused renewable mega-project targets FID in 2026, accessed June 12, 2025

[314] Middle East Ammonia Market Size, Share & Trends Report - 2032, accessed June 12, 2025,

[315] Marubeni Signs a Long-Term Offtake Agreement for Green Ammonia Produced in Inner Mongolia, China, accessed June 12, 2025

[316] The Future of Ammonia Supply in Europe - KBR, accessed June 12, 2025,

[317] Ammonia Supply Outlook 2024: A Clean Takeover - BloombergNEF, accessed June 12, 2025

[318] Ammonia Market Report | Industry Analysis, Size & Growth Outlook, accessed June 12, 2025

4| ECONOMIC VIABILITY: GREEN AMMONIA PRODUCTION COSTS

4.1 | Detailed Cost Comparison of Green, Grey, and Black Ammonia Production ($/ton)

Green ammonia is significantly more expensive[319] than conventional ammonia:

- **Black Ammonia (Coal):** $250 - $500 per ton.
- **Grey Ammonia (Natural Gas):** $300 - $600 per ton.
- **Green Ammonia (Renewable Energy):** $600 - $1,400 per ton. As of early 2025, specific prices were $885 - $1,050 per ton.[320] This cost difference far exceeds the 20% threshold for "different technologies" in CDM Tool 24.

4.2 | Analysis of Key Cost Drivers for Green Ammonia

Higher costs for green ammonia stem from:

- **Capital Expenditure (CAPEX):** Significant upfront investment in renewable energy infrastructure and electrolyzers.
- **Energy Costs:** Renewable energy, while decreasing, is often more expensive than natural gas, and intermittency requires additional storage investments. Electricity is over 90% of operational costs.
- **Technology Maturity and Scale:** Electrolysis and integrated renewable systems are less mature and scalable than conventional methods, leading to higher per-unit costs.

4.3 | Projected Cost Reductions for Green Ammonia by 2030

Green ammonia costs are projected to drop to $480 per tonne by 2030.[321] While this is a notable reduction, it remains at the higher end of traditional ammonia costs ($110-$340/tonne). Thus, without external incentives, green ammonia is unlikely to be cost-competitive by 2030.

5| IMPACT OF CARBON REVENUE AND POLICY MECHANISMS

5.1 | Overview of Global Carbon Pricing Mechanisms (ETS, Carbon Taxes, Crediting Mechanisms)

Carbon pricing, including Emissions Trading Systems (ETS), carbon taxes, and crediting mechanisms, covers about 28% of global GHG emissions. In 2024, carbon pricing mobilized over $100 billion for public budgets.[322]

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319 Ammonia production cost breakdown - ResearchGate, accessed June 12, 2025

320 Can ammonia propel the shipping industry toward a zero-carbon, accessed June 12, 2025

321 Green Ammonia – An Alternative Fuel - FutureBridge, accessed June 12, 2025

322 State and Trends of Carbon Pricing 2025 - World Bank, accessed June 12, 2025

5.2 | Required Carbon Price for Green Ammonia Competitiveness

A carbon price of approximately **$100-$150 per ton of CO2** is necessary for green ammonia to achieve price parity with fossil fuels by the early 2030s. Current global average carbon prices are well below this.[323]

5.3 | Influence of Policy Support (Subsidies, Tax Credits, Mandates)

Policy support is crucial:

- **Subsidies/Tax Credits:** The US Inflation Reduction Act (IRA) offers up to $3/kg for clean hydrogen.[324]
- **R&D Funding & Co-financing:** Supports early-stage projects.[325]
- **Demand-side Policies:** Mandates for green ammonia use (e.g., EU's FuelEU Maritime Regulation, 42% renewable hydrogen in fertilizers by 2030) create assured markets. [326]
- **Carbon Border Adjustment Mechanism (CBAM):** EU's CBAM, effective 2026, will require imported carbon-intensive goods, including ammonia, to comply with EU carbon pricing, incentivizing decarbonization.

These policies are critical for green ammonia to achieve price parity, potentially between 2030 and 2035.

5.4 | Current State of Carbon Credit Markets and Their Role

Carbon credit markets provide financial incentives, but supply exceeded demand in 2024, leading to a pool of nearly 1 billion unretired credits. While compliance market demand increased, prices softened.[327] The voluntary carbon market was valued at $2 billion in 2023, projected to grow to $50 billion by 2030. However, current carbon revenues are insufficient to drive green ammonia to common practice by 2030 without additional, targeted policy support.

6| COMMON PRACTICE ASSESSMENT FOR GREEN AMMONIA (2025-2030)

The common practice assessment for green ammonia, using UNFCCC CDM Tool 24, requires meeting two quantitative criteria: Factor F > 0.2 and (Nall - Ndiff) > 3.

6.1 | Quantitative Assessment for 2025

As of March 2025, only four green fertilizer projects are operational globally.[1] Even if all are considered "similar" (Ndiff = 0), (Nall - Ndiff) = 4, barely meeting the "greater

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[323] Carbon Pricing and the Economics of Green Ammonia, accessed June 12, 2025

[324] Clean hydrogen production credit | Internal Revenue Service, accessed June 12, 2025

[325] Can ammonia propel the shipping industry toward a zero-carbon, accessed June 12, 2025

[326] Can ammonia propel the shipping industry toward a zero-carbon, accessed June 12, 2025

[327] State and Trends of Carbon Pricing 2025 - World Bank, accessed June 12, 2025,

than 3" threshold. However, green ammonia's cost ($600-$1,400/ton) is significantly higher than conventional ammonia ($250-$600/ton), exceeding the 20% "different technologies" threshold. This economic difference, coupled with distinct production methods, means conventional plants are "different technologies." Given the vast dominance of conventional ammonia, green ammonia is far from common practice.

6.2 | Quantitative Assessment for 2030

By 2030, the "Advanced Projects scenario" projects operational green ammonia capacity at ~14 Mt, representing about 6.6% of total global ammonia production (210.81 Mt).[328] This limited penetration is insufficient for "common practice."

- **Cost Difference:** Projected costs of $480/tonne by 2030 are still at the higher end of conventional ammonia costs, maintaining a significant "different technologies" classification.
- **Technological Difference:** The fundamental difference in production methods (renewable electrolysis vs. fossil fuels) will persist.
- **Market Preference:** Blue ammonia projects are more advanced in FID, indicating they are currently a more viable "clean" alternative for investors, further limiting the "Nall" count for *green* ammonia.

Based on these factors, green ammonia will remain a "different technology" and not common practice by 2030 without carbon revenue.

7| CONCLUSION: UNLIKELY TO BE COMMON PRACTICE WITHOUT CARBON REVENUE

Green ammonia production facilities are highly unlikely to achieve common practice status by 2030 without substantial carbon revenue, as per UNFCCC CDM Tool 24. The current operational footprint is negligible (0.3% of global production, 4 projects), failing the common practice criteria for 2025.

By 2030, even with projected growth to 14 Mt, green ammonia will only constitute about 6.6% of the global market. The persistent cost disparity (green ammonia 2-6 times more expensive than conventional), even with projected reductions, means it will remain a "different technology" under CDM Tool 24 due to the >20% cost difference. The market's preference for blue ammonia, evidenced by faster FID rates, further segments the "clean" ammonia market, preventing green ammonia from achieving broad commonality.

The need for a carbon price of $100-$150 per ton of CO_2 for green ammonia to achieve price parity underscores its reliance on external incentives. Current global carbon pricing is insufficient. Without robust carbon revenue and comprehensive

[328] Ammonia Market Report | Industry Analysis, Size & Growth Outlook, accessed June 12, 2025

policy support (subsidies, tax credits, mandates), green ammonia projects face significant financial hurdles, leading to delays and cancellations.

To accelerate green ammonia's adoption, stronger and more widespread carbon pricing, sustained policy support (e.g., US IRA 45V, EU CBAM), and demand-side policies are essential. Without these, green ammonia will remain a niche technology, and projects seeking carbon credits during 2025-2030 will likely demonstrate additionality based on their non-common practice status.

Given the overwhelming evidence presented in this analysis, which confirms that green ammonia production is highly unlikely to become common practice globally by 2030 without significant carbon revenue, it is recommended that the Gold Standard consider streamlining the common practice analysis for such nascent, high-cost, and strategically important decarbonization technologies. Specifically, the methodology could exempt Green Ammonia project from the need to conduct project level common practice analysis.

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Contact Details

The Gold Standard Foundation
International Environment House 2
Chemin de Balexert 7-9
1219 Châtelaine Geneva, Switzerland
Tel +41 22 788 70 80
Email help@goldstandard.org

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