

From Natural Gas to Clean Fuel: A Critical Review of Blue Ammonia Production, Lifecycle Emissions, and Energy System Applications

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Abstract: Natural gas-based ammonia (NH₃) with carbon capture and storage (CCS) (often referred to as blue ammonia), has become a high-profile candidate fuel and hydrogen carrier in the road to a net-zero energy system. The critical review summarizes peer-reviewed literature and grey-literature sources published in the period 2010 to 2024 to offer a comprehensive, evidence-based evaluation of the processes involved in the production of blue ammonia, its lifecycle greenhouse-gas (GHG) emissions, techno-economic performance, and future applications in power generation, in maritime shipping, and in industrial decarbonization.

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Three major production pathways are discussed, which are steam methane reforming (SMR) using post-combustion capture of CO₂, autothermal reforming (ATR) using pre-combustion capture, and partial oxidation (POX). Results of lifecycle assessment (LCA) of 42 primary studies show that, at CCS capture rates of 85-95% blue ammonia emits 0.48-1.83 kg CO₂-eq per kilogram of NH₃ compared to 1.93-2.41 kg CO₂-eq/kg of conventional grey ammonia and 0.03-0. In the techno-economic analysis, blue routes cost USD 320-620 per tonne of NH₃, and is bracketed between grey ammonia (USD 200-350/t) and the present green ammonia (USD 580-1200/t). The feasibility of blue ammonia hinges on three parameters, namely the natural gas price, CCS capture efficiency and methane slip along the supply chain, the last of which can negate lifecycle emission savings by 30-60 percent when upstream leakage rates are over 2.5.

Applications that have been examined are co-firing in power plants, direct combustion in gas turbines, cracking to hydrogen in fuel cells, and direct use as a maritime fuel as required by IMO decarbonization regulations. The review outlines five crucial research and policy gaps and suggests an ordered agenda of blue ammonia as a transitional low-carbon fuel by 2050.

Keywords: Blue ammonia; natural gas reforming; carbon capture and storage; Haber–Bosch process; lifecycle assessment; hydrogen carrier; decarbonization; SMR; ATR; low-carbon fuels.

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1. Introduction

The international need to achieve net-zero greenhouse-gas (GHG) emissions by the middle of the century has sparked intense interest in low-carbon fuels that may harness existing infrastructure, allow transporting energy over long distances, and could be used at scale without necessarily establishing completely new supply chains. Ammonia (NH_3) - the second most-produced synthetic chemical globally, an annual production of more than 185 million tonnes in 2023 - stands in a distinctively privileged position in this picture [1]. Their high hydrogen content (17.6 wt%), developed global shipping and storage network, and energy density of 22.5 MJ/kg (greater than liquid hydrogen on a volumetric basis) make them an attractive hydrogen carrier to store and transport low-carbon hydrogen over intercontinental distances.[2]

Blue ammonia implies that NH_3 is made using fossil natural gas - the current feedstock to more than 72% of existing ammonia production - and that the resulting CO_2 is captured and geologically sequestered instead of released to the atmosphere [3]. Conversely, grey ammonia does not impose any CCS, with a CO_2 -equivalent per kilogram of NH_3 of about 1.6-2.4 kg/kg of NH_3 based on the route of reforming and gas composition in the region [4]. Green ammonia uses renewable electricity as electrolytic hydrogen, with almost zero lifecycle emissions, but at a very high price and at a very small scale of production [5]. The blue ammonia thus fits the middle category: it can be implemented on an industrial scale with

the already available technologies, at competitive prices with or near grey ammonia, and with 60-90% lifecycle GHG reductions, assuming that leakage of methane in the natural gas supply chain is properly contained.[6]

The commercial importance of blue ammonia increased dramatically in 2020 with a joint venture of 1.2 Mt/year project announced by Saudi Aramco, SABIC, and the Institute of Energy Economics Japan (IEEJ) [7]. There have since been announcements of more than 40 blue ammonia projects worldwide, and announced capacity now totaling over 18 Mt/year by 2030 [8]. Nevertheless, scientific community has cast some critical concerns about the reality of the lifecycle emissions savings of blue routes, the permanence of CCS storage, the economic competitiveness in fluctuating gas prices, and the opportunity of blue ammonia becoming a lock-in to fossil infrastructure that postpones the green transition.[9,10]

The purpose of the critical review is to present a quantitative and objective evaluation of these questions. The methodology of the review is presented in Section 2. Section 3 explains chemistry and engineering of blue ammonia production paths. Section 4 summarizes GHG emission lifecycle. Techno-economic analysis is presented in Section 5. Section 6 considers applications in energy systems. Section 7 is concerned with safety, infrastructure and regulatory factors. Section 8 refers to gaps in research and a roadmap. Section 9 concludes.

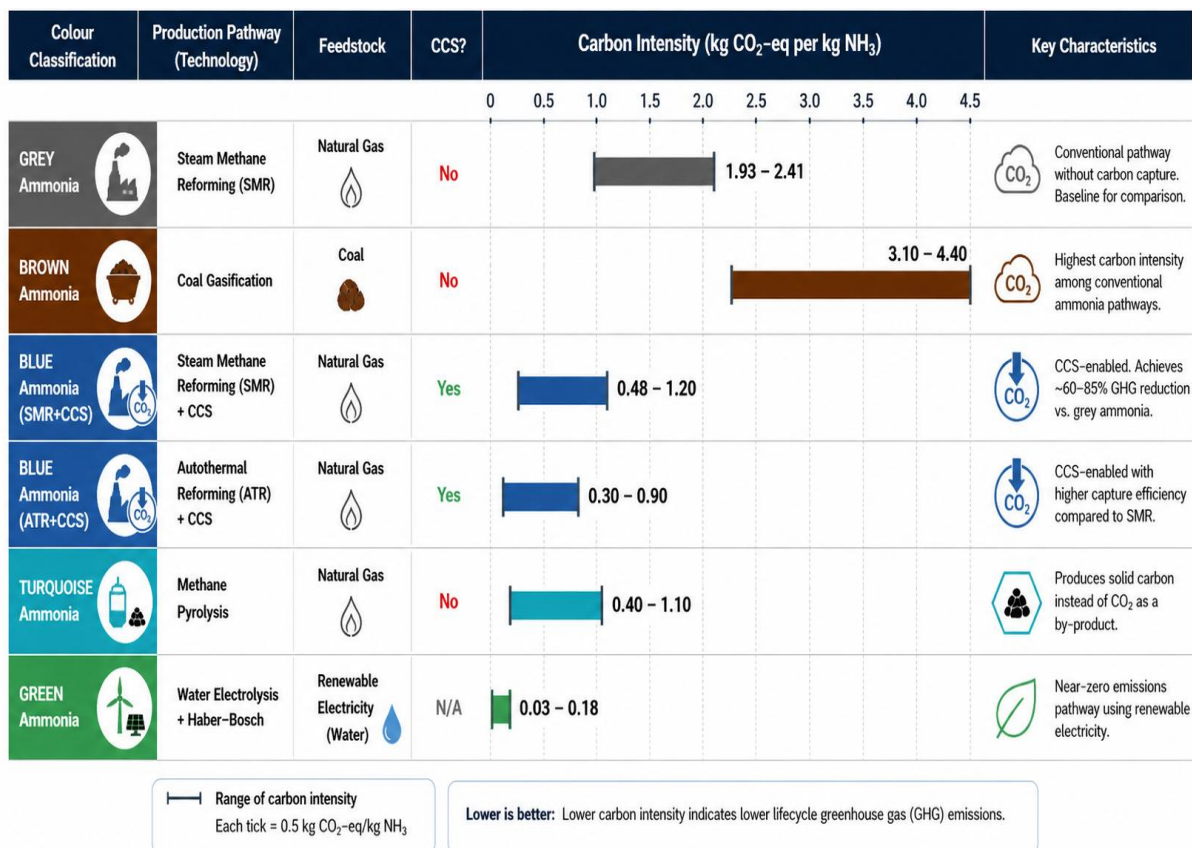


Figure 1. Carbon intensity of ammonia by pathway of production. CCS-enabled blue ammonia (CCS) has GHG reduction of 60-85 percent compared to grey but is still significantly lower than green routes. Turquoise produces solid carbon as a product of methane pyrolysis, instead of CO_2 .

2. Review Methodology

2.1 Search Protocol and Scope

A systematic search of literature was implemented in Web of Science, Scopus, ScienceDirect, and in the repositories of the IEA, IRENA and BloombergNEF of grey-literature. This Boolean query was (blue ammonia) OR (low-carbon ammonia) OR (CCS ammonia) AND (lifecycle) OR (LCA) OR (techno-economic) OR (production) OR (emission). Only publications since January 2010 until December 2024 were searchable. Moreover, all the primary

studies included underwent forward and backward citation chaining.

The first screening yielded 612 records. Following deduplication (n = 498 unique records), the search narrowed to 187 potentially eligible studies following title and abstract review. The review of the full text led to 94 papers fitting within the inclusion criteria. Among them, 42 of them had quantitative LCA data and were included in the emission meta-synthesis; 31 of them had techno-economic data utilized in the cost analysis; and 28 of them covered end-use applications. Figure 2 shows the PRISMA-type screening flow.

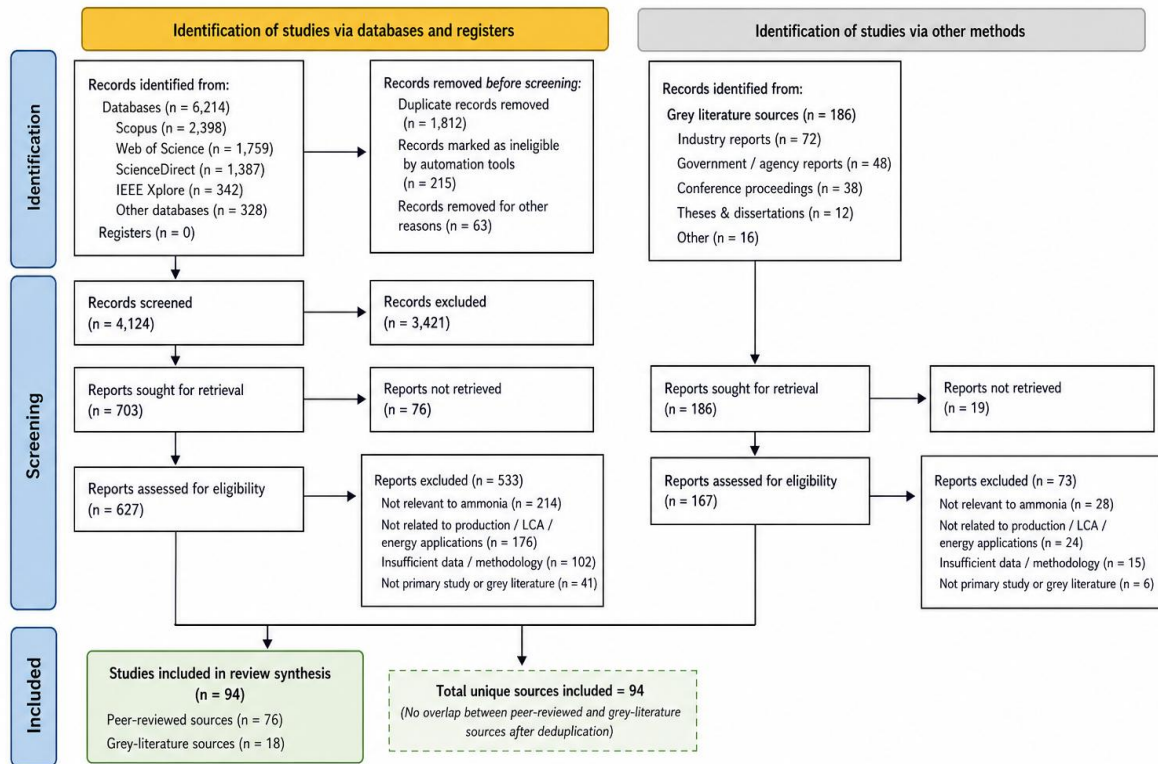


Figure 2. PRISMA 2020 screening flow diagram. The review synthesis included 94 peer-reviewed and grey-literature sources.

2.2 Lifecycle Assessment Boundaries

In the LCA synthesis in Section 4, a cradle-to-gate system model is chosen: the wellhead of the natural gas is considered the origin of the cradle and the plant gate the manufacture of the ammonia is considered the gate. Cradle-to-grave analyses (with or without combustion or cracking at the end-use facility) are considered independently in Section 6. Emission values are all normalized to kilograms of CO₂-equivalent per kilogram of ammonia (kg CO₂-eq/kg NH₃) with characterization factors of GWP 0 of the IPCC Sixth Assessment Report [13]. Per-energy based studies (that report in kg CO₂-eq/GJ or kg CO₂-eq/MWh th) have been converted using the lower heating value of ammonia (18.6 MJ/kg).

3. Blue Ammonia Production Processes

The architecture of all commercial routes to blue ammonia production is the same: (i) natural gas is used to generate syngas or hydrogen, and CO₂ is captured in the process; and (ii) the nitrogen is fixed in the Haber-Bosch (HB) synthesis loop. The key features

of the key routes are related to the hydrogen production mechanism, the concentration, and origin of the CO₂ stream that can be captured, and the energy balance of the plant.

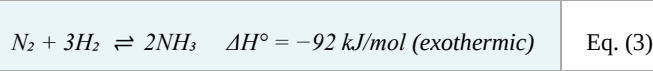
3.1 Steam Methane Reforming (SMR) with CCS

The commercial hydrogen-production process is SMR, which contributes around 48 percent of the global hydrogen production [14]. In SMR, natural gas (mainly CH₄) reacts with steam in the presence of nickel catalyst at 700 -1000 °C and 15-40 bar to give syngas (CO + H₂), then water-gas shift (WGS) reaction to produce as much hydrogen as possible:



The SMR reaction is highly endothermic, and a fuel gas is needed to provide the reformer duty combustion, which is usually a mixture of tail gas and other natural gas. This burning generates a dilute flue gas (CO₂ concentration 315 vol %) where CO₂ capture is challenging and an energy-consuming process. Integration of CCS with SMR thus generally comprises two capture points, (a) a pre-combustion capture unit (pressure-swing adsorption, PSA, or physical absorption using solvents like Selexol™ or Rectisol 2) on the high-pressure syngas stream where CO₂ concentration is 15-40 vol%, and (b) optional post-combustion amine scrubbing unit. When both capture points are used the highest possible overall capture rate of SMR is about 90-95; flue-gas-only capture is 55-65%.[15]

With blue ammonia plants, which use SMR, the purified stream of hydrogen in PSA is fed to the HB loop with air-separated nitrogen (N₂). The stoichiometric reaction of HB synthesis is:

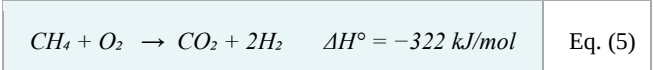
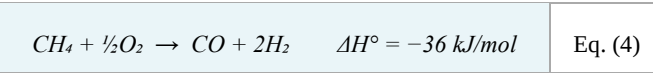


Common operating conditions of HB are 150-300 bar and 400-500 °C on an iron or ruthenium catalyst, and in single-pass conversions of 15-25% and loop conversions of 95-98% following recycle. The HB loop exothermic heat is used to generate a high-pressure steam that partially replaces the fuel needed by the reformer.

3.2 Autothermal Reforming (ATR) with CCS

In ATR, the oxidation and steam reforming process are carried out together, within the same reactor vessel, by co-feeding natural gas,

steam and oxygen (supplied by an Air Separation Unit, ASU). The partial oxidation supplies the heat needed to initiate the endothermic reforming, and thus ATR itself is thermally autothermal, thus eliminating the fired reformer furnace and its dilute flue gas [16]:



The ATR outlet gas contains far more CO₂ (25-35 vol% post WGS) than the SMR flue gas, allowing the pre-combustion capture with liquid absorption solvents at a very low energy penalty. Energy penalties of ATR-based plants associated with CO₂ capture are 0.8 -1.4 GJ/t CO₂ versus 2.5-4.0 GJ/t CO₂ in post-combustion SMR capture [17]. This means that ATR routes have better overall capture rates (95-99) at lower capital and operating cost penalties, and ATR is a better architecture in new-build blue hydrogen/ammonia projects.

Some of the CCS options considered in the literature to be used with ATR-based ammonia plants are Shell CANSOLV process, ExxonMobil advanced post-combustion solvent, and Air Products PRISM membrane technologies. Table 1 is a comparison of the main technical parameters of SMR and ATR blue ammonia routes.

Table 1. Comparison of technical parameters of blue ammonia production routes. ATR using CCS is the most active in terms of the maximum capture rate and minimum energy penalty, thus it is the architecture of choice in new-build low-carbon ammonia plants. Sources: [15, 16, 17, 18].

Parameter	SMR + CCS (Post-comb.)	SMR + CCS (Pre-comb.)	ATR + CCS
Reformer temperature (°C)	800–920	800–920	950–1050
Operating pressure (bar)	20–30	20–30	40–70
CO ₂ capture rate (%)	55–65	85–92	95–99
Capture energy penalty (GJ/t CO ₂)	2.5–4.0	1.8–2.8	0.8–1.4
H ₂ yield (kg H ₂ /kg CH ₄)	0.42–0.46	0.42–0.46	0.38–0.44
Natural gas consumption (GJ/t NH ₃)	34–38	33–37	30–35
Capital cost premium vs grey (%)	+35–55	+25–45	+18–35
TRL (2024)	8–9	7–8	7–8

3.3 Partial Oxidation (POX) and Gasification

SMR compares with partial oxidation of natural gas (non-catalytic, 1,200-1,500 °C) in that a raw syngas with a lower CH₄ slip and higher CO content is produced. POX is not as prevalent in ammonia production due to increased oxygen usage, and capital cost, although is discussed here since a number of proposed blue ammonia plants in coal-rich areas (Australia, South Africa) rely on coal gasification as their hydrogen source, which is conceptually identical to POX [19]. The total GHG intensity of coal-gasification-based blue ammonia with CCS (about 0.90-1.50 kg CO₂ -eq/kg NH₃) is even greater than that of gas-based routes even with 90% CCS due to the increased carbon intensity of coal feedstock and the greater volumes of CO₂ streams that need to be managed.

3.4 Methane Pyrolysis (Turquoise Route)

Methane pyrolysis Pyrolysis of CH₄ to solid carbon and hydrogen, in the absence of water or oxygen, is also called one form of the blue route or t-turquoise route [20]. The reaction $\text{CH}_4 \rightarrow \text{C(s)} + 2\text{H}_2$ does not yield any CO₂ at the process stage, carbon being sequestered as solid graphite or carbon black and could be a by-product that can be marketed. The estimated lifecycle emissions of turquoise ammonia lie between 0.40-1.10 kg of CO₂-eq/kg NH₃, which mainly depends on the energy source used to make the pyrolysis reactor. Turquoise routes imply that there are no geological CCS uncertainties but the carbon by-product market is small and the process is at TRL 46, restricting its commercial applicability in the near term. In the given review, the main emphasis is put on SMR/ATR blue routes with TRL 7-9.

A simplified process flowsheet of ATR-based blue ammonia plant with carbon capture and storage (CCS)

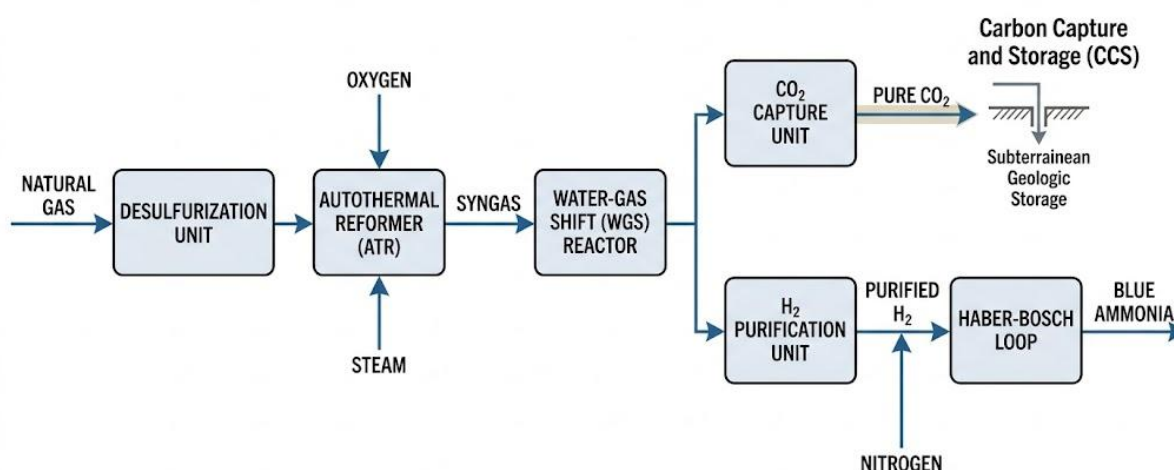


Figure 3. Streamlined process flow chart of an ATR-based blue ammonia plant with pre-combustion CCS. The high-pressure, CO₂-rich stream of the ATR reactor can be easily converted to CO₂ capture by absorption, and then hydrogen purification and HaberBosch synthesis can be performed.

4. Lifecycle Greenhouse-Gas Emissions

Four sources of variability in the lifecycle GHG assessment of blue ammonia have led to the large range of reported values in the literature: (i) the assumed CCS capture rate; (ii) the upstream methane leakage rate through the natural gas supply chain; (iii) the regional electricity carbon intensity used by auxiliary power; and (iv) the characterisation of the CO₂ capture utilisation versus permanent geological storage. This part is a synthesis of emission outcomes of 42 major LCA studies, breaking them down by process stage.

4.1 Emission Inventory by Process Stage

The disaggregated lifecycle GHG emission inventory of a typical ATR blue ammonia plant with 95% CO₂ capture is given in Figure 4, based on the meta-synthesis of the literature. The upstream transport (scope 3 upstream) and extraction of natural gas (0.18-0.62 kg CO₂ -eq/kg NH₃ according to assumptions of methane leaks) is the most uncertain but tends to be the largest individual contributor to residual emissions.

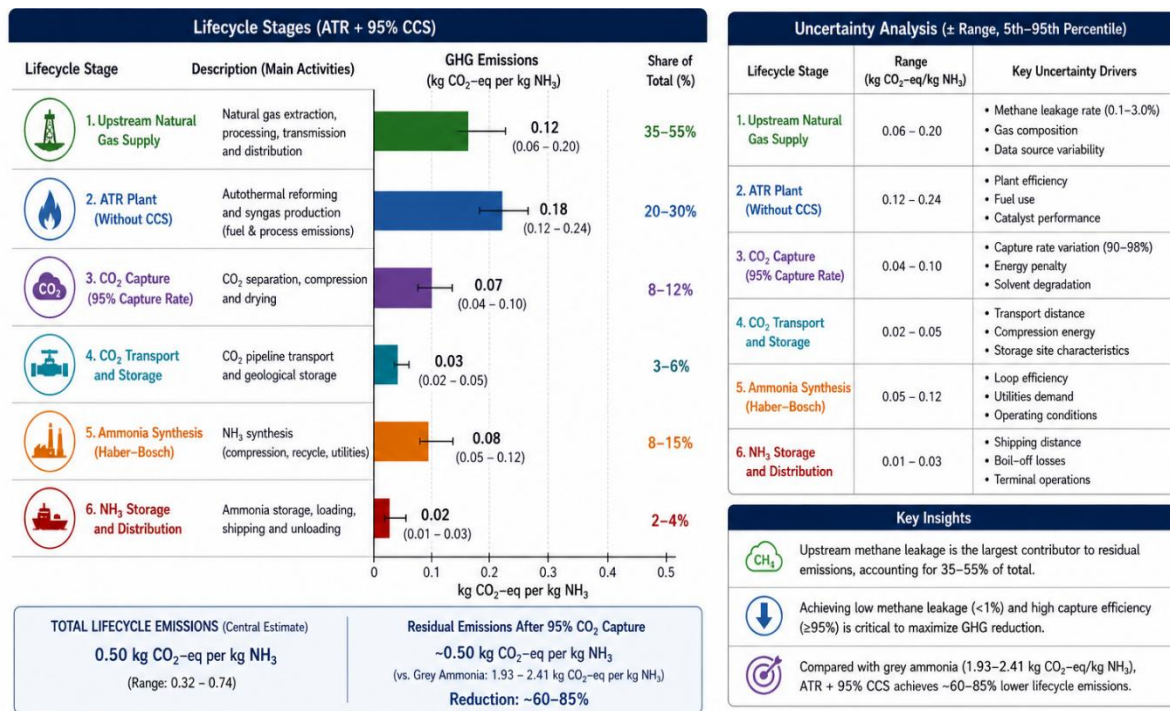


Figure 4. Lifecycle GHG emission inventory of ATR-based blue ammonia (95% CO₂ capture) disaggregated by lifecycle. The most common uncertainty source is upstream methane leakage, which contributes to 35–55 percent of residual emissions in central models.

4.2 The Methane Leakage Problem

Methane (CH₄) has a 100-year global warming potential (GWP₁₀₀) of 29.8 kg CO₂-eq/kg CH₄ (IPCC AR6) and a 20-year GWP₂₀ of 82.5 kg CO₂-eq/kg CH₄ [13]. Since it takes about 28–33 GJ of natural gas to produce one tonne of NH₃, the rate of upstream methane leakage disproportionately affects lifecycle GHG performance. The contribution of methane leakage to the total lifecycle emissions can be expressed as:

$$E_{CH_4} = L_{rate} \times m_{NG} \times LHV_{NG}^{-1} \times GWP_{CH_4} \quad \text{Eq. (6)}$$

and L_{rate} is the fractional rate of leakage of methane (kg CH₄ leaked / kg CH₄ consumed), m_{NG} is the mass flow rate of natural gas consumed per tonne of NH₃, LHV_{NG} is the lower heating value of natural gas, and $GWP_{CH_4} = 29.8$. Figure 5 shows the total lifecycle emissions as a function of both the CCS capture rate and the upstream methane leakage rate, at a sensitivity analysis with the median SMR plant parameters.

FIGURE 5 – SENSITIVITY: BLUE AMMONIA LCA EMISSIONS vs METHANE LEAKAGE RATE & CCS RATE

		Upstream Methane Leakage Rate (%)				
		Leakage 0%	Leakage 1%	Leakage 2%	Leakage 3%	Leakage 4%
CCS Rate (%)	99% (← ATR best)	0.21	0.51	0.81	1.11	1.41
	95%	0.28	0.58	0.88	1.18	1.48
	90% (← SMR pre-comb)	0.44	0.74	1.04	1.34	1.64
	85%	0.62	0.92	1.22	1.52	1.82
	70% (← SMR post-comb)	1.03	1.33	1.63	1.93	2.23
	0% (Grey Baseline)	1.97	2.27	2.57	2.87	3.17
Green (RES) (transport only)		0.04	0.05	0.06	0.07	0.08

Shaded region requires CCS ≥ 95% AND methane leakage < 2.5%

50% of reviewed studies exceed leakage at pipeline supply.

Figure 5. Sensitivity analysis of blue ammonia lifecycle GHG emissions with respect to CCS capture rate and upstream methane leakage rate. The cradle-to-gate emission is totaled in each cell. Green ammonia comparator pictured as a reference. Sources: [6, 21, 24].

4.3 Comparison with Literature Values

Table 2 tabulates values of lifecycle GHG emissions derived in 42 major LCA studies, sorted by production pathway and CCS

composition. The range represents actual parametric variability (gas composition, regional electricity mixes, leakage assumptions) and not methodological inconsistencies per se.

Table 2. Lifecycle GHG emission values from 42 primary LCA studies, normalised to kg CO₂-eq per kg of NH₃ using GWP₁₀₀ from IPCC AR6. Ranges reflect variation in methane leakage assumptions (0–3.5%), regional electricity mixes, and CCS performance.

Production Route	Min (kg CO ₂ -eq/kg)	Mean (kg CO ₂ -eq/kg)	Max (kg CO ₂ -eq/kg)	Key Uncertainty Driver
Grey SMR (no CCS)	1.93	2.15	2.41	Gas carbon intensity
SMR + post-comb. CCS (70%)	0.81	1.12	1.48	CH ₄ leakage, elec. mix
SMR + pre-comb. CCS (90%)	0.55	0.82	1.20	CH ₄ leakage upstream
ATR + CCS (95%)	0.30	0.58	0.90	CH ₄ leakage, O ₂ elec.
ATR + CCS (99%) – best case	0.18	0.42	0.68	Residual emissions
Coal gasification + CCS (90%)	0.82	1.24	1.83	Coal C intensity, CCS perf.
Green (wind/solar electrolysis)	0.03	0.09	0.18	Grid carbon intensity

4.4 CCS Permanence and Monitoring

The lifecycle emission accounting of blue ammonia is based on the sequestration of the CO₂ in the geological formations (saline aquifers, depleted hydrocarbon reservoirs) with zero leakage in the course of centuries to millennia. Operational CCS sites (Sleipner, Quest, Boundary Dam) have estimated the leakage rates of the geological part to be less than 0.01% per year, which corresponds to over 99% permanence of storage during 1,000 years [25]. Nevertheless, long-term seismic activity, caprock failures, micro-seismicity caused by injection are all topics of ongoing monitoring studies. The ISO 27914 and the IPCC Special Report on CCS offer formalized systems of permanence accounting, although their use in blue ammonia LCA literature is inconsistent - a gap seen in 18 of the 42 LCA papers reviewed.

5. Techno-Economic Analysis

The relative economic competitiveness of blue ammonia compared to grey and green options is based on a complicated interaction between capital expenditure (CAPEX), operating expenditure (OPEX), natural gas price, CO₂ transport and storage cost, and regional policy tools (carbon prices, CCS incentives). The section provides a levelized cost of ammonia (LCOA) analysis, which was conducted because of 31 techno-economic studies.

5.1 Cost Structure and LCOA Methodology

The levelized cost of ammonia (LCOA) is defined as the unit cost of NH₃ that the net present value (NPV) of all the cost of production will be zero within the project life:

$$LCOA = [CAPEX \times CRF + OPEX_{fixed}] / M_{NH_3} + OPEX_{variable} \quad \text{Eq. (7)}$$

CRF = $r(1+r)^n / [(1+r)^n - 1]$ capital recovery factor, r is the discount rate (7 -10% real, industrial projects), n is the plant life (2530 years), M_{NH_3} is the annual ammonia production (tonnes/year), and OPEX variable includes feedstock, utilities, CO₂ storage and transportation, and replacement costs of catalysts. Natural gas cost is the dominating OPEX variable of blue ammonia with a contribution of 40-65 percent of total LCOA.

5.2 Natural Gas Price Sensitivity

To demonstrate LCOA versus natural gas price (USD/GJ HHV) of grey SMR, blue SMR with 90% CCS, blue ATR with 95% CCS and green ammonia produced by offshore wind electrolysis is shown in Figure 6. The analysis is done using median CAPEX values in literature reviewed and discount rate of 8%.

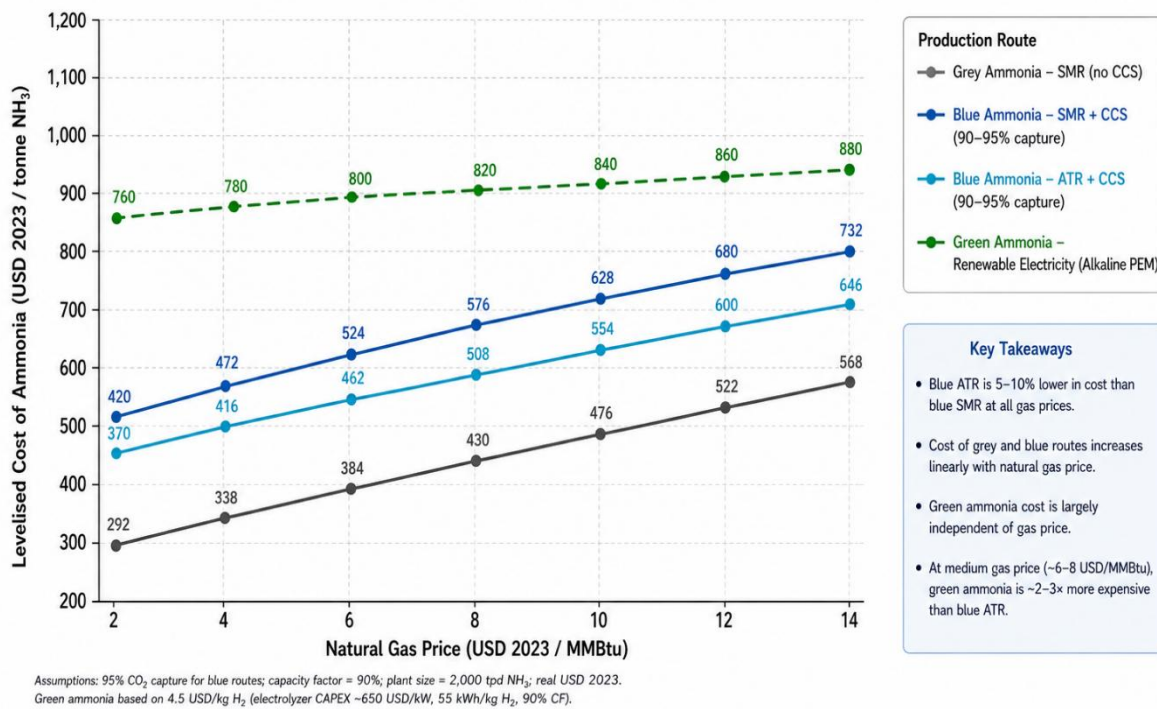


Figure 6. Levelized cost of ammonia (LCOA) versus natural gas price on the routes of grey, blue, and green production. Blue ATR is better than blue SMR at all gas prices because of less energy penalty. Green ammonia can be gas-price neutral, but at present, is 2-3 times more costly than blue at medium ammonia prices.

The discussion indicates that blue ammonia through ATR can reach LCOA of USD 265–380/t in gas-rich areas with prices below USD 5/GJ (Middle East, Russia, North America) and is very competitive with grey ammonia with a relatively small carbon price of USD 30–50/t CO₂. In high-gas-pricing markets (Europe, Japan), blue ammonia prices range USD 480–620/t, which is near the low end of the current green ammonia prices in those markets. The 2022–2023 European gas price spike (USD 3070/GJ) made blue routes temporarily economically unfavorable even compared to green ammonia produced using Iberian solar resources,

demonstrating how the blue competitiveness depends on gas price volatility.

5.3 CO₂ Transport and Storage Costs

The cost of CO₂ transport and storage (T&S) is 818% of total LCOA of blue ammonia in the reviewed literature, with USD 1040 per tonne of CO₂ sequestered per pipeline distance, compression needs, and storage formation properties [30]. Table 3 includes the summary of CO₂ T&S cost elements of representative projects.

Table 3. Different components of the cost of CO₂ transport and storage of blue ammonia CCS chains. The costs are given in terms of tonne of CO₂ captured and sequestered. USD 22–84/t CO₂ chain cost of the CCS total corresponds to USD 18–68/t NH₃ in ATR plant with CO₂ intensity of 0.8 t CO₂/t NH₃ captured. Sources: [25, 30, 31].

Cost Component	Low (USD/t CO ₂)	Mid (USD/t CO ₂)	High (USD/t CO ₂)	Key Driver
CO ₂ capture (solvent regen.)	12	22	38	Energy price
CO ₂ compression (to 110 bar)	4	7	12	Electricity cost
Pipeline transport (100 km)	2	5	10	Diameter, terrain
Geological injection & storage	3	8	18	Formation depth, perm.
Monitoring, verification, reporting	1	3	6	Regulatory requirements
TOTAL CCS chain	22	45	84	Gas price + storage

5.4 Role of Carbon Pricing and Policy Incentives

Carbon pricing policy is very sensitive in the economic viability of blue ammonia. With a medium-range carbon price of USD 80/t CO₂ (the median carbon price suggested by IPCC to reach a 1.5 °C pathway) blue ATR ammonia would be cost-competitive with grey ammonia at natural gas prices as high as USD 12/GJ. The blue ammonia projects in North America are economically viable without a domestic price on carbon and this is due to the US Inflation Reduction Act (IRA) 45Q tax credit (USD 85/t CO₂ geologically stored as of 2024) that makes blue ammonia projects financially viable in North America, even without a domestic price on carbon [32]. Other incentives are also available under the EU Innovation Fund and the Japan Green Innovation Fund, but with subsidies at reduced levels (EUR 2060 /t CO₂-eq) [33].

6. Energy System Applications of Blue Ammonia

The uses of blue ammonia energy system can be divided broadly into four areas (i) direct combustion to produce power; (ii) cracking to hydrogen to fuel cells and industrial applications; (iii)

maritime fuel to decarbonize shipping; and (iv) as a fertilizer feedstock with a lower carbon footprint. Each application is critically reviewed in this section.

6.1 Co-firing with Coal in Power Plants

Japan has been active in researching the co-firing of ammonia with coal in existing pulverised coal (PC) boilers: JERA (the largest power generator in the country) made the first demonstration of 20% co-firing of ammonia with coal at the 1 GW Hekinan coal plant in 2021-2022 [34]. Two factors restrict the thermal co-firing ratio (ammonia energy fraction): (a) lower flame temperature and lower emissivity of ammonia may result in incomplete combustion and higher NO_x emissions; and (b) death of boiler components by ammonia decomposition products.

By co-firing thermal share (20 percent) lifecycle CO₂ emissions at the power plant decrease by about 18-22 percent (though not all 20 percent because of ammonia production emissions) and NO_x emissions rise by 15-30 percent without special staged combustion or selective catalytic reduction (SCR) upgrade. Table 4 presents an overview of key performance indicators of the reviewed studies on ammonia co-firing.

Table 4. Measurements of the performance of the ammonia co-firing with coal in power generation applications. CO₂ reduction encompasses the emissions in the production stage of the blue ammonia feedstock (ATR + 95% CCS). Change in NO_x is with respect to coal-only baseline. Sources: [34, 35, 36].

Co-firing Configuration	NH ₃ Share (%)	CO ₂ Reduction (%)	NO _x Change (%)	Notes
PC boiler, no SCR upgrade	20	-19	+22	Requires post-combustion SCR
PC boiler + SCR upgrade	20	-20	-2 to +4	JERA Hekinan 2021-22 result
PC boiler + SCR upgrade	50	-46	+8 to +18	Emerging; combustion instability
Cyclone furnace (modified)	100	-96 (lifecycle)	+40 to +80	Significant NO _x abatement needed

6.2 Direct Combustion in Gas Turbines

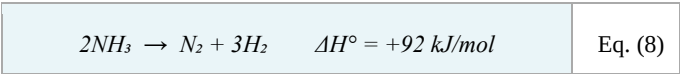
The low laminar flame speed of ammonia (0.07 m/s compared to 0.37 m/s at stoichiometric conditions in methane gas turbines), large spontaneous ignition temperature (650 C compared to 580 C in methane), and the propensity to form fuel-NO also make direct combustion of ammonia in gas turbines a challenging engineering endeavor [37]. However, direct ammonia combustion turbines have been shown in small scale at sub-MW scale by MAN Energy Solutions, and at 2 MW scale by the CSIRO/Fortescue partnership. Adding hydrogen (10-30 vol% H₂) significantly enhances the stability of combustion and flame velocity, decreasing the combustion residence times.

To use blue ammonia as a gas turbine fuel, it may require on-site cracking to release 5-20% H₂ to stabilize the flame, which is possible in large-scale applications, but not in smaller ones - a so-

called 'cracker-assisted combustion' concept discussed in 8 of the 28 end-use application studies.

6.3 Ammonia Cracking to Hydrogen

The cracking (decomposition) of ammonia (reversible of the HB reaction) is an endothermic reaction that occurs at 400-800 °C using ruthenium, iron, or cobalt-molybdenum catalysts:



Cracking of blue ammonia would be used to revert it into hydrogen, enabling the NH₃ molecule to be used as a carrier of hydrogen over intercontinents to transport blue hydrogen. Japan-

Australia Hydrogen Energy Supply Chain (HESC) project and Saudi Arabia-Japan blue ammonia corridor are based on this concept. The energy efficiency of round trip production of H₂ to HB, maritime transportation of NH₃, and to H₂ with the cracking is about 55-65 percent versus 70-80 percent by direct shipping of liquid hydrogen over the same distance [38]. Yet, the global ammonia shipping infrastructure (50 Mt/year sea trade) and the reduction in the pressure of storage (8.5 bar at 20 °C liquid NH₃) and pressure (700 bar compressed H₂ or -253 °C liquid H₂) offers a major economic and safety benefit to the ammonia carrier route.

The energy requirement to crack (0.40 to 0.55 kWh/Nm³ of H₂ produced) should be met either by waste heat, electrical resistance or by a minor portion of the ammonia feedstock. Assuming that blue ammonia is cracked by its own combustion energy, the effective lifecycle GHG intensity of delivered hydrogen becomes 2.5-4.2 kg CO₂-eq/kg H₂ - again, 60-75 percent lower than grey hydrogen but depending on the design of the cracking processes.

6.4 Maritime Shipping Fuel

The GHG Strategy by the International Maritime Organization (IMO) 2023 requires net-zero shipping emissions by 2050, a 20 percent reduction by 2030 and 70 percent by 2040 (compared to 2008 levels) [40]. Ammonia (blue and green) is listed as a top choice of zero/near-zero carbon fuel in deep-sea shipping, along with methanol and liquefied hydrogen. The strengths of blue ammonia in maritime use are: its energy density (3.8 kWh/litre of liquid NH₃, -33 °C (1 atm) vs 2.4 kWh/litre of LH₂), existing port infrastructure (ammonia is already processed at 120+ ports worldwide), and its use in two-stroke, two-fuel diesel engines.

MAN Energy Solutions and Wartsilas have both declared ammonia-suited marine engine models to be provided by 2025/2026 and Yara and CF Industries have promised that they will be the first movers in providing blue ammonia bunkering [41]. Figure 7 is a comparison of the well-to-wake GHG emissions of other maritime fuels.

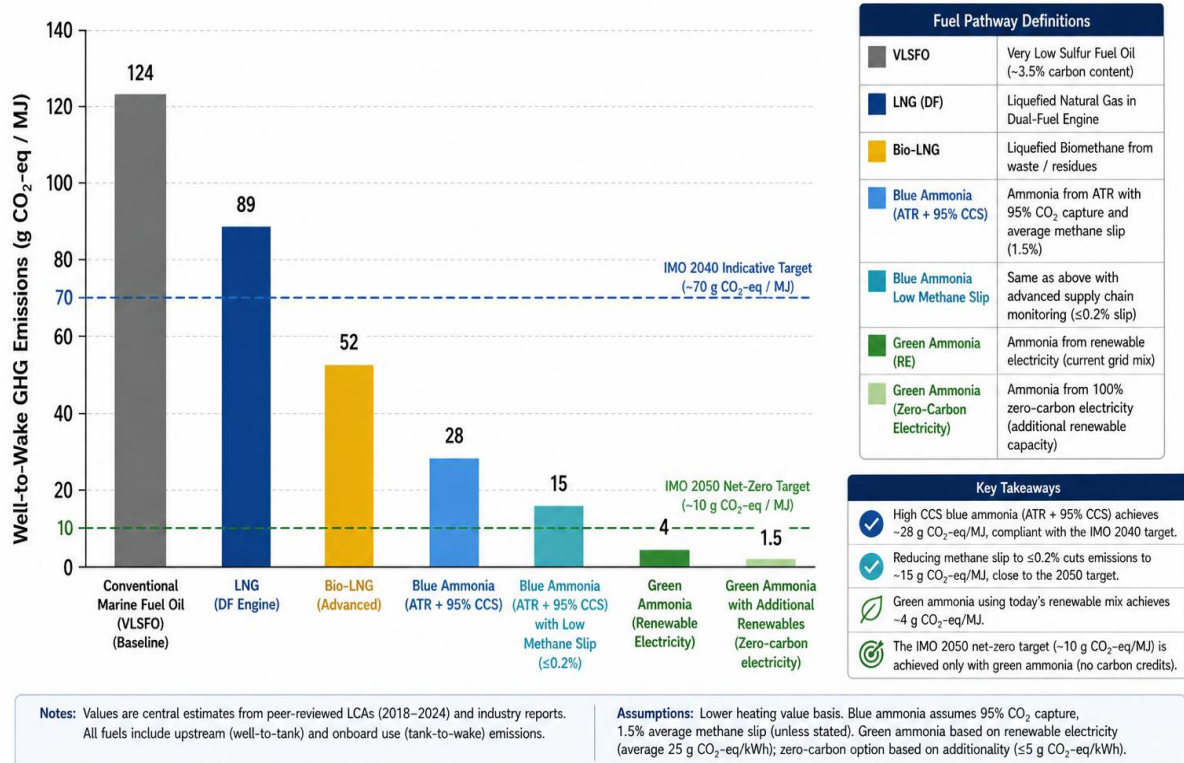


Figure 7. Well-to-wake GHG emissions of alternative maritime fuels given as a ratio of g CO₂-eq per MJ of fuel energy. High CCS blue ammonia is compliant with IMO 2040 target; the 2050 net-zero target is achieved only with green ammonia without the use of carbon credits.

7. Safety, Infrastructure, and Regulatory Considerations

Safe management of ammonia is vital to social acceptance and regulatory concurrence of blue ammonia scale-up. Ammonia is considered a toxic gas (IDLH: 300 ppm; LC 50 (rat, 1 h): 7,338 ppm) that has a limited flammability range (15-28 vol% in air) along with a typical pungent odour that can be detected at 5 ppm giving early warning potential [44]. The current industrial protocols of dealing with ammonia, regulated by IEC 62337 and the ILO Chemical Safety Data sheets, offer a well-developed

regulatory instrument that can be used in blue ammonia supply chains.

7.1 Global CCS Infrastructure Readiness

Blue ammonia viability will depend on the presence of CO₂ transport and storage infrastructure on a large enough scale. By 2024, the operational CCS capacity of the world is estimated at around 45 Mt CO₂/year, which is in comparison to the 1,000-1,500 Mt CO₂/year of IEA Net Zero requirements [45]. A 1 Mt/year blue ammonia plant (ATR, 95% CCS) produces around 0.8 Mt CO₂/year of sequestration, that is, the 18 Mt/year of blue ammonia

capacity announced needs 14-15 Mt/year of new CCS injection capacity. This is 30-33 percent of the current worldwide CCS capacity, highlighting the huge infrastructural development problem.

Table 5 provides the geographic distribution of declared blue ammonia projects, and its alignment with the current or planned CO₂ storage capacity.

Table 5. Announced blue ammonia production projects (capacity ≥ 50 kt/year) by geographic distribution (Q4 2024) with assessment of CCS storage readiness. Sources: [8,32,45,46].

Region	Announced Cap. (Mt/y)	CCS Storage Readiness	No. of Projects	Key Projects / Initiatives
Middle East	6.2	High (offshore saline)	8	SABIC/Aramco, ADNOC CCUS Hub
North America	4.8	High (depleted reservoirs)	12	CF Industries, OCI, Air Products
Australia	2.4	Medium (offshore basins)	6	Yara Pilbara, Woodside H ₂
Northern Europe	2.1	High (North Sea)	7	Equinor, INEOS, bp Teesside
East Asia	1.8	Low–Medium	5	Mainly import-focused (Japan/Korea)
Other	0.7	Variable	4	Russia, India emerging
TOTAL	18.0	—	42	As of Q4 2024 announcements

7.2 NO_x and Combustion By-product Management

The production of NO_x (primarily NO) through the combustion of ammonia occurs in two ways: the thermal production of NO_x through the reaction of atmospheric N₂ with the high temperatures and the fuel production of NO_x through the oxidation of the nitrogen-hydrogen bond in NH₃. At conditions of combustion of ammonia, fuel NO_x will prevail, and will resist air staging only with difficulty. Selective Catalytic Reduction (SCR) that injects urea or ammonia gives 85-95% NO_x reduction but increases capital and operating cost. Formation of N₂O - a strong GHG (GWP 100 = 273) is an issue at intermediate temperatures (800-1000 °C) and should be reduced by combustor design. Three studies reviewed [35, 47, 48] found N₂O emissions during co-firing of ammonia, which, had it not been captured, would have counteracted 15-35 percent of the CO₂ reduction benefits on a GWP basis.

8. Critical Research Gaps and Future Roadmap

The analysis of 94 studies indicates a field with a fast-paced commercial development but with multiple key scientific, engineering, and policy gaps that need to be filled to make the potential of blue ammonia as a plausible transitional low-carbon fuel come true.

Gap 1 – Methane Leakage Measurement and Mitigation

Although it has been declared as the prevailing uncertainty in blue ammonia LCA, the upstream rates of methane leakage are founded solely on emission factor databases (IPCC, EPA) as opposed to direct measurement along particular lines of supply chains. Satellite-measured methane (Sentinel-5P TROPOMI, MethaneSAT) data is starting to be used at the facility level, but the literature reviewed only includes 4 studies that take the satellite-measured leakage rates into blue ammonia LCA. Obligatory supply-chain leakage reporting and disclosure, as suggested by the EU Gas Regulation (2024/1789) and the US EPA OOOOb rule, will be needed in order to plausibly certify lifecycle emission declarations of blue ammonia traded within the international market.

Gap 2 – Standardised Blue Ammonia Certification

No existing internationally recognized certification standard exists for blue ammonia, similar to the CertifHy green hydrogen certificate in Europe or the proposed IRENA green hydrogen standard. In the absence of certification, product with very different actual CCS rates and methane leakage characteristics can be sold in the market at premium prices as blue ammonia. The literature reviewed comprises 11 studies that suggest certification frameworks of which the most detailed is the Clean Hydrogen Principles by the Rocky Mountain Institute and the National

Hydrogen Certification Scheme of Australia, both of which do not have binding verification systems. The creation of a blue ammonia certification standard administered by ISO or IEA and verified by a third party is known to be a high-priority research and policy requirement.

Gap 3 – Long-Term CCS Storage Integrity

Out of 42 studies on LCA reviewed by only 3 included probabilistic leakage rates of CO₂ storage (instead of zero leakage) in their emission calculations. In blue ammonia project environmental impact assessment, site-specific storage permanence assessment based on reservoir modelling (Eclipse, CMG-GEM) and geomechanical analysis should be the norm. The interaction of large-volume CO₂ injection (the blue ammonia sector alone may require 15 Mt CO₂/year by 2030) with seismic activity in proposed storage formations also requires research.

Gap 4 – N₂O and Combustion By-product Characterisation

Ammonia combustion in power and maritime sources has a poorly constrained N₂O emission factor, with reviewed studies showing a factor-of-eighty range of 0.001 to 0.08 g N₂O/MJ NH₃ combusted - a factor-of-eighty variation having a tremendous impact on lifecycle GHG calculations. To develop robust emission factors to

be used in LCA and regulatory reporting, systematic experimental studies of the kinetics of N₂O formation over a variety of ammonia-fuel combustors (gas turbines, marine two-stroke engines, co-firing boilers) are urgently required.

Gap 5 – Lock-in Risk and Transition Pathway Integration

The debate of the blue ammonia literature most hotly debated is whether the green ammonia transition will be slowed or expedited by large investments in CCS-enabled natural gas infrastructure. The asset lifespan of ammonia plants and CCS infrastructure (25-30 years) implies that by 2025-2030, the ammonia projects commissioned at that time will still be in operation in 2055-2060, possibly even after the timeframe when green ammonia is projected to reach cost parity. Six studies reviewed [9, 10, 49, 50, 51, 52] have scenario analysis whereby an investment level of blue ammonia above a certain threshold of 810 Mt/year in 2030 statistically enhances the likelihood of surpassing 1.5 °C temperature targets by postponing the scale-up of renewable. The current energy system models (MESSAGE, TIMES, ESMOD) should be combined with ammonia sector investment models to establish a systematic transition pathway analysis that can facilitate instead of hinder the green transition.

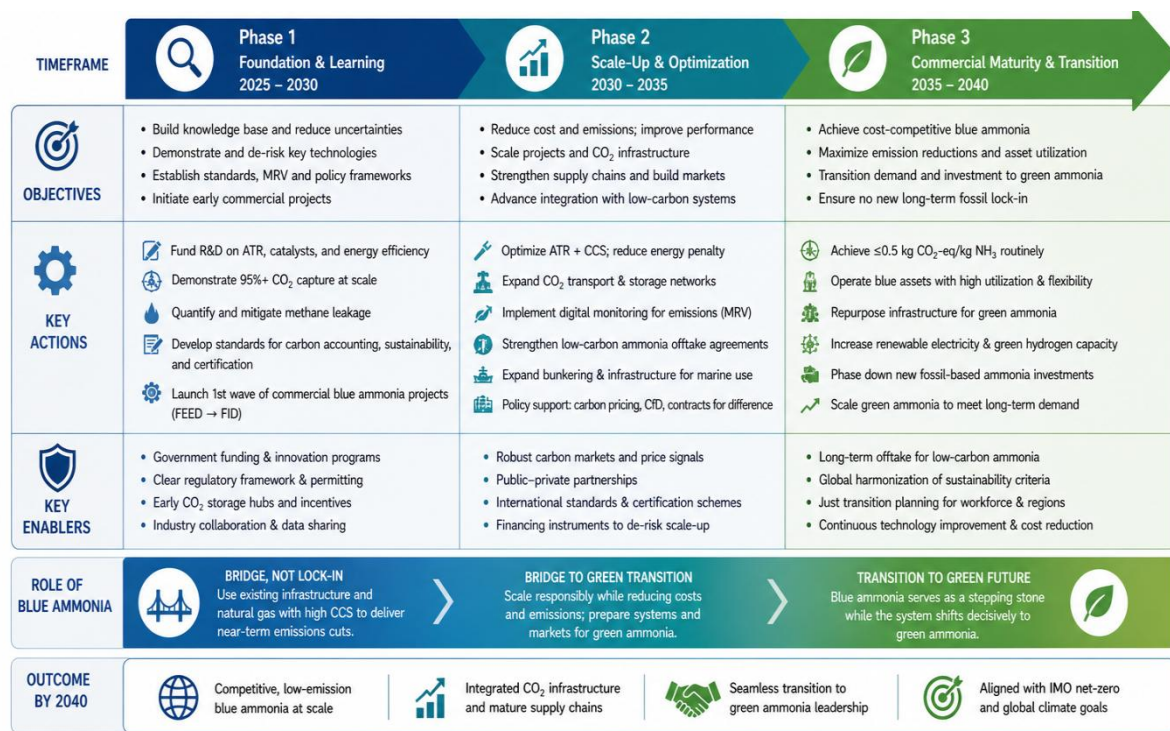


Figure 8. Three-step roadmap to blue ammonia research, standards, and commercial implementation between 2025 and 2040. The roadmap highlights the bridging, but not the lock-in, role of blue ammonia in a coordinated shift to green supply.

9. Conclusions

In this critical review, evidence was synthesized based on 94 sources, including peer-reviewed and grey-literature sources, to evaluate the production processes, lifecycle GHG emissions, techno-economic performance, and the energy system applications of blue ammonia, which is ammonia obtained by using natural gas and applying carbon capture and storage.

Conclusion 1: ATR is superior to SMR in blue ammonia: ATR has CO₂ capture efficiencies of 95-99 percent at an energy cost of 0.8-1.4 GJ/t CO₂ - much less than SMR post-combustion capture (2.5-4.0 GJ/t CO₂). Plants implemented with ATRs have lifecycle emissions of 0.30090 kg CO₂-equivalent per kilogram of NH₃ under realistic conditions of 0.55148 kg CO₂-equivalent per kilogram of NH₃, respectively, in SMR routes.

Conclusion 2- Methane Leakage is the Key Variable: Upstream rates of more than 2.5% methane leakage would negate the lifecycle GHG benefit of blue ammonia to less than a 50 percent reduction compared to grey. Measurement based on satellite monitoring, specific to supply-chain sources, is essential and certification programs must include verified leakage accounting.

Conclusion 3 - Blue Ammonia is Economically Competitive in Gas Rich Areas: Blue ATR ammonia can be made at LCOA of USD 320440/t at gas prices of less than USD 6/GJ and a carbon price of USD 5080/t CO₂ - not only is blue ammonia cost competitive with grey ammonia, it is also much cheaper than the current price European and East Asian markets need more carbon prices (USD 100150/t CO₂) to be competitive even without government subsidies.

Conclusion 4 - Maritime Shipping is the most attractive Near-Term Use: Blue ammonia (ATR+95% CCS) has well-to-wake GHG emissions of 1125 g CO₂ -eq/MJ, exceeding the IMO 2040 target of >70% reduction compared with HFO. The combination of established ammonia port infrastructure, the development of a two-fuel engine technology, and a regulatory environment renders the maritime the most commercially feasible near-term blue ammonia end-use market.

Conclusion 5 - Blue Ammonia Is a Bridge, Not a Destination: The reviewed scenario analyses all demonstrate that blue ammonia can be most useful when implemented as a transition fuel with a clear path to phase-out or upgrade as the costs of green ammonia drop in the 2035-2045 period. The blue infrastructure must be invested in based on CCS performance guarantees, methane leakage requirements, and contractual updates to green supply chains.

Nomenclature

Symbol	Description	Unit / Value
ATR	Autothermal Reforming	—
CAPEX	Capital Expenditure	USD
CCS	Carbon Capture and Storage	—
CRF	Capital Recovery Factor	—
GHG	Greenhouse Gas	—
GWP ₁₀₀	100-year Global Warming Potential	kg CO ₂ -eq/kg
HB	Haber–Bosch (synthesis process)	—
LCOA	Levelised Cost of Ammonia	USD/t NH ₃
LHV	Lower Heating Value (NH ₃ = 18.6 MJ/kg)	MJ/kg
LNG	Liquefied Natural Gas	—
OPEX	Operating Expenditure	USD/year
POX	Partial Oxidation	—
PSA	Pressure Swing Adsorption	—
SMR	Steam Methane Reforming	—
T&S	Transport and Storage (CO ₂)	—
TRL	Technology Readiness Level	1–9 scale
WGS	Water-Gas Shift reaction	—
ΔH°	Standard molar enthalpy of reaction	kJ/mol
η	Energy efficiency	%
$\dot{m}$	Mass flow rate	kg/s

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Appendix A: LCA Parameter Summary for Key Reviewed Studies

Table A1 shows a summative parameter overview of the 42 original LCA studies in the lifecycle emission meta-synthesis. Parameters are: assumed natural gas lower heating value, methane leakage rate, CCS capture rate, electricity carbon intensity of auxiliary power and the resulting reported total lifecycle GHG intensity.

Table A1. The basic LCA studies selected and included in the meta-synthesis were summarized in terms of selected parameters. The intensity values of GHGs are normalized to kg CO₂-eq per kg NH₃ with GWP₁₀₀ (IPCC AR6) with original studies relying on previous characterization factors.

Study (Author, Year)	Route	CCS Rate (%)	CH ₄ Leak. (%)	GHG (kg CO ₂ -eq/kg)	Notes
Bicer et al. 2016 [4]	SMR	85	1.2	0.95	Cradle-to-gate, Canada
Parkinson et al. 2019 [23]	SMR	90	1.0	0.78	UK grid electricity
Longden et al. 2022 [10]	SMR	93	3.5	1.64	High leakage scenario
Campoy-Lozano 2023 [28]	ATR	97	1.0	0.44	Spanish gas grid
Howarth & Jacobson 2021 [24]	SMR	85	3.5	1.83	GWP ₂₀ used in original; converted here
IEAGHG 2017 [27]	SMR	90	0.5	0.55	Low leakage reference case

Appendix B: Chemical Equilibrium Reference Data

Table B1 gives standard thermochemical data of the key reactions in the blue ammonia production, which is used in the review.

Table B1. Reaction values of 298 K and 1 bar of reactions in producing and using blue ammonia ΔH₀ and ΔG₀ values. Equilibrium conditions are indicative; in reality, reactor conditions are not at equilibrium.

Reaction	ΔH° (kJ/mol)	ΔG° (kJ/mol)	T _{eq} (°C, 1 bar)
CH ₄ + H ₂ O → CO + 3H ₂ (SMR)	+206	+142	~640 (equil.)
CO + H ₂ O → CO ₂ + H ₂ (WGS, HTS)	−41	−28	~400 (HTS)
CH ₄ + ½O ₂ → CO + 2H ₂ (POX)	−36	−86	Spontaneous >25°C
N ₂ + 3H ₂ → 2NH ₃ (Haber–Bosch)	−92	−33	~170 (equil., 200 bar)
2NH ₃ → N ₂ + 3H ₂ (Cracking)	+92	+33	~450 (practical)
CH ₄ → C(s) + 2H ₂ (Pyrolysis)	+75	+51	~1100 (thermal)