

Integration of Green Ammonia Pipelines with Renewable Energy Systems

Ashok Kumar¹, Kuldeep Sharma^{2*}, Vineet Yadav³

¹Welspun Tubular Inc., Little Rock, AR, USA

²Dura-Bond Industries, Pittsburgh, PA, USA

³Born Inc., Tulsa, OK, USA

Email: *ksmb3112@gmail.com

How to cite this paper: Kumar, A., Sharma, K. and Yadav, V. (2025) Integration of Green Ammonia Pipelines with Renewable Energy Systems. *Smart Grid and Renewable Energy*, 16, 177-185.

<https://doi.org/10.4236/sgre.2025.169010>

Received: July 24, 2025

Accepted: October 20, 2025

Published: October 23, 2025

Copyright © 2025 by author(s) and Scientific Research Publishing Inc.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The rising demand for sustainable energy solutions has intensified interest in green ammonia as a promising energy carrier. Produced using renewable energy sources, green ammonia offers a viable alternative for industrial and energy applications due to its efficient transportability via pipelines. This review examines the integration of green ammonia pipelines with renewable energy systems, focusing on production technologies, transportation logistics, economic feasibility, and environmental advantages. It also underscores the pivotal role of policy and regulatory frameworks in ensuring successful implementation and widespread adoption.

Keywords

Green Ammonia, Renewable Energy Integration, Ammonia Pipelines, Energy Storage, Decarbonization, Economic Feasibility

1. Introduction

The global energy landscape is rapidly transitioning toward decarbonization, driving the need for innovative energy storage and transportation solutions [1] Schmuecker & Mertens (2021). Green ammonia, produced from renewable hydrogen [2] Smith & Liu (2020) and atmospheric nitrogen, emerges as a promising candidate for long-term energy storage and sustainable fuel applications. This review explores the potential of green ammonia pipelines [3] Jones & Williams (2019) as a critical component of renewable energy infrastructure, assessing their feasibility [4] Patel & Gomez (2022), advantages, and role in enabling a low-carbon future [5] UNEP (2021).

2. Green Ammonia Production and Properties

Green ammonia is produced through electrolysis-driven hydrogen generation and subsequent ammonia synthesis via the Haber-Bosch process, powered by renewable energy [6] Bora *et al.* (2022). Its high energy density, carbon-free combustion, and ability to be liquefied for storage and transportation make it attractive [7] Chehade & Dincer (2021). However, production efficiency and scalability remain active areas of research. These technologies are illustrated in **Figure 1**.

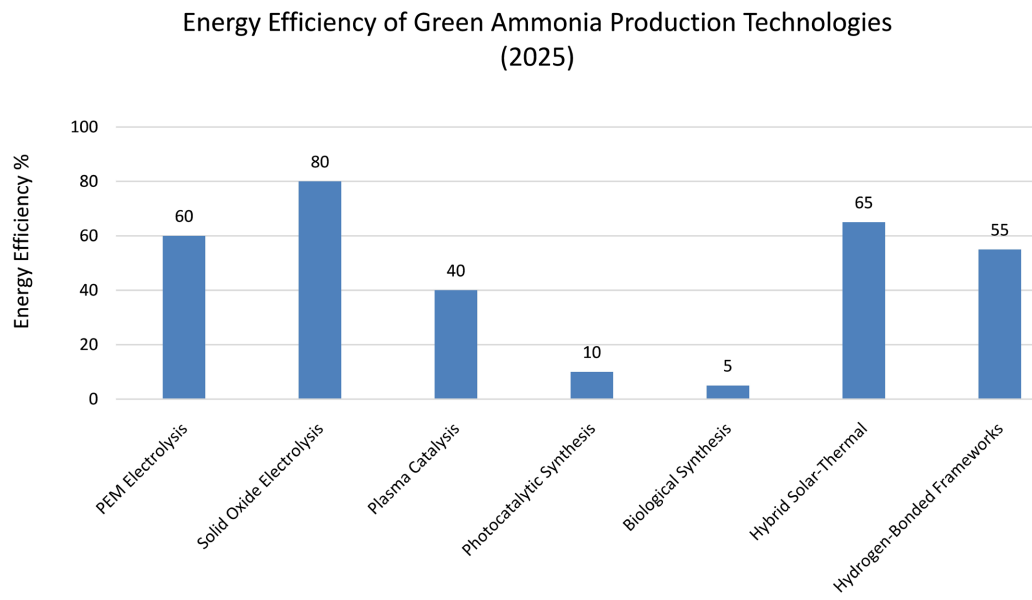


Figure 1. Emerging production technologies.

Overview of ammonia's chemical and physical properties

It is a colorless, pungent-smelling gas composed of one nitrogen atom covalently bonded to three hydrogen atoms. It is one of the most widely produced industrial chemicals globally, used extensively in fertilizers, refrigerants, and as a precursor to many nitrogen-containing compounds.

Physical Properties

- Molecular Formula: NH_3
- Molar Mass: 17.03 g/mol
- Appearance: Colorless gas
- Odor: Pungent, characteristic
- Melting Point: -77.7°C
- Boiling Point: -33.34°C
- Density: 0.73 kg/m^3 at 0°C and 1 atm
- Solubility: Highly soluble in water ($\sim 89.9 \text{ g/100 mL}$ at 0°C)

Ammonia is a polar molecule, with a trigonal pyramidal molecular geometry resulting from the lone pair on nitrogen. This polarity contributes to its high solubility in water due to hydrogen bonding interactions.

Chemical Properties

Basicity

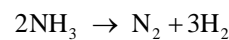
Ammonia acts as a weak base in aqueous solution, forming the ammonium ion (NH_4^+):



Its base dissociation constant K_b is approximately 1.8×10^{-5} at 25°C

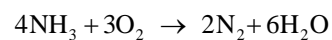
Reactivity

Ammonia readily forms complexes with transition metals due to its lone pair, acting as a ligand in coordination chemistry. It also reacts with acids to form ammonium salts and decomposes at high temperatures into nitrogen and hydrogen gases: [8] Cotton *et al.* (1999).



Combustion

Ammonia can combust in the presence of oxygen:



This exothermic reaction forms the basis of ammonia as a potential clean fuel alternative [9] Lan *et al.* (2012).

2.1. Emerging Production Technologies (2025)

PEM Electrolysis + Renewable Integration: Proton Exchange Membrane (PEM) electrolyzers use renewable electricity to split water into hydrogen and oxygen. Known for high responsiveness and efficiency (55% - 65%), they are ideal for intermittent renewable energy systems [10] Kurien & Mittal (2022).

Solid Oxide Electrolysis (SOE): High-temperature electrolysis (700°C - 1000°C) uses solid oxide fuel cells to produce hydrogen with thermal assistance. Efficiency can exceed 80% when integrated with waste heat or solar thermal systems, though durability and material degradation remain key challenges.

Plasma Catalysis: Non-thermal plasma accelerates nitrogen fixation and ammonia synthesis under ambient conditions, allowing for decentralized, low-energy production. Current research is focused on improving energy efficiency and catalyst performance.

Photocatalytic Ammonia Synthesis: Semiconductor-based photocatalysts (e.g., TiO_2 , BiVO_4) harness solar energy to directly reduce nitrogen. While promising, solar-to-ammonia conversion efficiencies remain low, with major advancements required in catalyst design and light absorption [11] Zhang, Wang & Li (2021).

Biological Nitrogen Fixation: Utilizing nitrogen-fixing bacteria (e.g., Azotobacter) and engineered microbial systems to produce ammonia under ambient conditions. Synthetic biology is enhancing ammonia yields and control, making it viable for localized production.

Hydrogen-Bonded Frameworks (HOFs/MOFs): Porous frameworks improve hydrogen storage and water splitting, reducing energy demands in the hydrogen-

to-ammonia conversion chain. These are being explored to enhance overall system efficiency.

Hybrid Solar-Thermal + Electrolysis Systems: Combines concentrated solar power (CSP) with electrolysis to provide both electricity and heat for ammonia synthesis, increasing total system efficiency and enabling operations in solar-rich regions.

To better understand the viability of various emerging technologies for green ammonia production, it is essential to compare their performance metrics. The following table (**Table 1**) summarizes key production methods, highlighting their typical efficiency ranges, primary advantages, and major challenges, providing a clear overview for assessing scalability and integration with renewable energy sources.

Table 1. Efficiency of green ammonia production methods.

Production Method	Typical Efficiency (%)	Key Advantages	Key Challenges
PEM Electrolysis + Haber-Bosch	55 - 65	Fast response, good for renewables	High CAPEX, low durability
Solid Oxide Electrolysis (SOE)	70 - 80	High efficiency, uses waste heat	Material degradation, high T (700°C - 1000°C)
Plasma Catalysis	30 - 40 (lab scale)	Operates at ambient conditions	Low efficiency, scaling issues
Photocatalytic Synthesis	<5	Direct solar-to-ammonia	Very low conversion, needs breakthroughs
Biological Nitrogen Fixation	10 - 15 (experimental)	Ambient conditions, sustainable	Low yield, scaling challenges
Hybrid Solar-Thermal + Electrolysis	65 - 75	Utilizes both heat & electricity	Complex integration, site-specific

Note: Efficiency ranges are based on reported laboratory and pilot-scale studies. SOE values assume partial utilization of waste heat or solar thermal integration [12] He, Liu & Zhao (2022) & [13] Beyrami *et al.* (2024). Biological nitrogen fixation and photocatalytic synthesis are at experimental stage; scalability remains uncertain.

2.2. Advantages and Scalability Enhancements

- **Engine Compatibility:** Green ammonia avoids hydrogen embrittlement in internal combustion engines, preserving component life [14] Sharma, Kumar, Yadav & Banerjee (2025) and [15] Kumar, Sharma, Yadav & Banerjee (2025).
- **Storage:** Ammonia liquefies at moderate pressure/temperature, unlike hydrogen which requires -253°C or high pressure.
- **Energy Density:** Ammonia has a higher volumetric energy density than hydrogen [16] Haynes (2014).
- **Modular Production:** Small-scale, modular plants powered by local renewables are reducing logistics costs.
- **Catalyst Improvements:** Ruthenium-based and iron-nitride catalysts enable synthesis at lower pressure/temperature.
- **Hybrid Storage Systems:** Ammonia is integrated with batteries/hydrogen to balance grids.

- **AI Optimization:** Digital twins and machine learning improve electrolysis and synthesis efficiencies.

3. Integration with Renewable Energy Systems

3.1. Infrastructure Development

Green ammonia infrastructure requires retrofitting existing pipelines and constructing new facilities. Retrofitting involves upgrading materials and adding monitoring systems. New infrastructure includes production hubs, storage terminals, and export pipelines. A coordinated dual-track investment approach can expedite the transition [17] Müller *et al.* (2024).

3.2. Current State of Green Ammonia Pipeline Development

At present, large-scale green ammonia pipeline infrastructure is still in its infancy compared to conventional oil, gas, and hydrogen networks. While feasibility studies and pilot projects are emerging in regions such as Europe, the Middle East, and Australia, most existing ammonia pipelines were originally designed for industrial fertilizer applications and are limited in length and capacity. This provides a partial foundation for future development, as certain safety standards, material compatibility guidelines, and regulatory frameworks are already in place. However, to fully integrate green ammonia pipelines into renewable energy systems, substantial retrofitting, scaling, and expansion will be required. Unlike starting entirely from scratch, this approach allows the industry to build upon existing ammonia handling experience, but with renewed emphasis on decarbonization, long-distance transport, and energy storage functions.

3.3. Storage and Transport

Ammonia is stored as a liquid under mild conditions but demands corrosion-resistant containment. Pipeline transport is efficient for large volumes but requires material compatibility and safety mechanisms. Alternatives include ship, rail, and truck transport in areas lacking pipelines.

3.4. Grid Balancing and Energy Storage

Ammonia enables long-term energy storage, unlike batteries, and supports dispatchable power generation during renewable lulls. It can be synthesized during surplus generation and used across power, transport, and industrial sectors, enhancing grid reliability.

To further validate the role of green ammonia in grid balancing, it is important to evaluate the economic trade-off between the cost of constructing ammonia synthesis and storage infrastructure and the financial benefit of utilizing otherwise wasted renewable power. During periods of excess generation, significant renewable electricity is curtailed due to grid limitations. Converting this surplus into ammonia not only prevents energy losses but also creates a storable and trans-

portable energy carrier. Preliminary studies indicate that, although capital expenditures for electrolyzers, storage tanks, and pipelines are substantial, the value recovered from reduced curtailment, enhanced grid stability, and cross-sectoral utilization (power, transportation, and industry) can result in a positive return on investment over the long term. A detailed cost-benefit analysis, factoring in regional renewable penetration and policy incentives, is therefore essential to strengthen the case for ammonia-based energy storage.

4. Challenges and Technical Considerations

4.1. Material Compatibility

Ammonia causes corrosion in traditional steel. Certified carbon-manganese or stainless steel is preferred. Plastics like HDPE and PP degrade, making them unsuitable. This increases vehicle fuel tank weight and complexity, especially in welding. Research into lightweight corrosion-resistant alloys and coatings is essential.

4.2. Safety Concerns

Ammonia is toxic, with strict safety protocols needed. Low explosion limits and occupational exposure thresholds demand continuous monitoring, advanced sensors, and emergency response systems.

Risk Assessment and Preventive Measures:

While ammonia presents significant opportunities as a carbon-free energy carrier, its inherent toxicity raises serious concerns for human health and the ecological environment. In the event of a pipeline leak or accidental release, exposure can cause respiratory distress, chemical burns, and long-term ecological damage, particularly to aquatic systems where ammonia can disrupt biodiversity. Therefore, risk assessments must account for both occupational hazards and broader community safety. Preventive measures include real-time leak detection sensors, double-walled pipelines, corrosion-resistant materials, and automated emergency shutoff valves. Additionally, comprehensive safety training, strict adherence to occupational exposure limits, and emergency response protocols are essential to minimize risks. Establishing environmental monitoring programs near critical infrastructure can further safeguard ecosystems from potential contamination.

Comparison with Hydrogen Safety Incidents

While hydrogen and ammonia are both promising carbon-free fuels, their safety profiles differ significantly and influence infrastructure requirements. Hydrogen is highly flammable, with a wide explosive range (4% - 75% in air) and numerous recorded incidents linked to leakage and ignition, particularly in high-pressure storage and transport systems. By contrast, ammonia is less prone to explosion but presents acute toxicity risks upon inhalation or environmental release. Historical industrial data indicate that hydrogen-related accidents are more fre-

quent in terms of fire and explosion events, whereas ammonia incidents are rarer but often associated with severe health or ecological impacts.

This comparison highlights the importance of tailoring risk mitigation strategies: for hydrogen, emphasis is placed on leak prevention and fire suppression, whereas for ammonia, continuous air monitoring, corrosion-resistant pipelines, and community safety protocols are more critical. Together, these insights reinforce the need for robust, technology-specific risk management frameworks as ammonia pipelines are scaled up [18] Lee, Lim, Lee & Lim (2021).

Addressing the safety implications of handling ammonia requires a thorough awareness of its toxicological limits and regulatory guidelines. The table below (Table 2) outlines critical toxicity parameters and safety thresholds established by organizations such as OSHA and NIOSH, serving as a reference for risk assessment and the implementation of preventive measures in pipeline and storage operations.

Table 2. Ammonia toxicity and safety thresholds.

Parameter	Value
Odor Threshold	~5 ppm (detectable smell)
OSHA Permissible Exposure Limit (PEL)	50 ppm (8-hr TWA)
NIOSH Immediately Dangerous to Life or Health (IDLH)	300 ppm
Short-Term Exposure Limit (STEL)	35 ppm (15 min)
Lethal Concentration (LC50, 1 hr, rat)	~2000 ppm

Note: Toxicity thresholds are sourced from OSHA (PEL, STEL), NIOSH (IDLH), and toxicological animal studies (LC50). Values are indicative and may vary depending on environmental and occupational exposure conditions.

4.3. Energy Efficiency

Ammonia synthesis is energy-intensive due to electrolysis. Transport and refrigeration further increase energy use. Efficiency improvements in catalysts and integration with renewables are critical.

4.4. Economic Viability

High capital costs for electrolyzers, pipelines, and storage infrastructure challenge economic viability. LCOA comparisons with grey and blue ammonia, policy incentives, and declining renewable costs will influence adoption. Regional market development and global trade agreements will be key.

Evaluating the economic competitiveness of green ammonia against other energy carriers is crucial for informed decision-making in sustainable energy transitions. The subsequent table (Table 3) provides a comparative snapshot of levelized costs, infrastructure requirements, and CO₂ emissions for green ammonia and its alternatives, illustrating the trade-offs and potential long-term benefits in a decarbonized energy landscape.

Table 3. Cost-benefit snapshot of green ammonia vs alternatives.

Carrier/Fuel	Levelized Cost (\$/kg H ₂ equivalent)	Infrastructure Needs	CO ₂ Emissions (kg CO ₂ /kg H ₂)
Grey Ammonia	1.0 - 1.2	Existing fertilizer pipelines	~9 - 11
Blue Ammonia	1.3 - 1.6	CCS facilities + transport	~2 - 3
Green Ammonia	2.5 - 3.5 (2025 est.)	Electrolyzers, new pipelines	~0
Compressed H₂	3.0 - 5.0	High-pressure tanks, pipelines	~0
Liquid H₂	4.0 - 7.0	Cryogenic infrastructure	~0

Note: Levelized cost values are expressed per kilogram of hydrogen equivalent for cross-comparison. Green ammonia costs reflect projected 2025 estimates assuming renewable electricity at 25 - 40 USD/MWh. Grey and blue ammonia costs are based on conventional natural gas feedstock with and without CCS, respectively.

5. Environmental and Economic Impacts

Green ammonia reduces CO₂ emissions by replacing fossil-derived hydrogen. It serves as a clean fuel in shipping, industry, and power. However, minimizing energy input and lifecycle emissions is essential. Economic viability depends on infrastructure cost, energy efficiency, and market dynamics. Carbon pricing, subsidies, and innovation will drive competitiveness.

6. Policy and Regulatory Framework

Supportive policies are vital. Incentives like subsidies, tax credits, and carbon pricing make green ammonia competitive. Funding R&D and pilot projects will advance technology and reduce costs. Regulatory clarity on safety, transport, and international harmonization will facilitate global trade and investment.

7. Conclusion and Future Perspectives

Green ammonia pipelines present a transformative opportunity for integrating renewable energy into global supply chains. They offer a viable solution for energy storage, transportation, and decarbonization. While technical and economic challenges persist, advances in electrolysis, materials science, and AI, combined with supportive policies, can accelerate deployment. Future efforts should focus on scaling up production, improving infrastructure, and establishing robust regulatory frameworks to realize ammonia's potential as a cornerstone of sustainable energy systems [19] Lee, Winter, Lee, Lim & Elimelech (2022).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Schmuecker, H. and Mertens, J. (2021) Advancements in Green Ammonia Production: A Review. *Renewable Energy Reviews*, **45**, 234-256.

- [2] Smith, R.J. and Liu, P. (2020) Electrolysis-Based Hydrogen Production for Ammonia Synthesis. *International Journal of Hydrogen Energy*, **45**, 5678-5692.
- [3] Jones, T. and Williams, L. (2019) Integration of Renewable Energy with Green Ammonia Pipelines. *Energy & Environmental Science*, **12**, 987-1002.
- [4] Patel, K. and Gomez, S. (2022) Economic Viability of Green Ammonia as a Sustainable Energy Carrier. *Journal of Energy Economics*, **56**, 765-781.
- [5] United Nations Environment Programme (UNEP) (2021) Green Ammonia: A Pathway to Carbon-Free Energy. UNEP Reports, 22, 1-50.
- [6] Bora, N., Singh, A.K., Pal, P., Sahoo, U.K., Seth, D., Rathore, D., *et al.* (2022) Green Ammonia Production: Process Technologies and Challenges. *Journal of Cleaner Production*, **334**, Article ID: 130163.
- [7] Chehade, G. and Dincer, I. (2021) Progress in Green Ammonia Production as Potential Carbon-Free Fuel. *Fuel*, **299**, Article ID: 120845.
<https://doi.org/10.1016/j.fuel.2021.120845>
- [8] Cotton, F.A., Wilkinson, G., Murillo, C.A. and Bochmann, M. (1999) *Advanced Inorganic Chemistry*. 6th Edition, Wiley-Interscience.
- [9] Lan, R., Irvine, J.T.S. and Tao, S. (2012) Ammonia and Related Chemicals as Potential Indirect Hydrogen Storage Materials. *International Journal of Hydrogen Energy*, **37**, 1482-1494. <https://doi.org/10.1016/j.ijhydene.2011.10.004>
- [10] Kurien, C. and Mittal, M. (2022) Review on the Production and Utilization of Green Ammonia as an Alternate Fuel in Dual-Fuel Compression Ignition Engines. *Energy Conversion and Management*, **251**, Article ID: 114990.
<https://doi.org/10.1016/j.enconman.2021.114990>
- [11] Zhang, X., Wang, Y. and Li, D. (2021) Photothermal Catalysis: From Principles to Applications. *Chemical Engineering Journal*, **419**, Article ID: 129409.
- [12] Beyrami, J., Nogueira Nakashima, R., Nemat, A. and Lund Frandsen, H. (2024) Degradation Modeling in Solid Oxide Electrolysis Systems: A Comparative Analysis of Operation Modes. *Energy Conversion and Management: X*, **23**, Article ID: 100653.
<https://doi.org/10.1016/j.ecmx.2024.100653>
- [13] Sharma, K., Kumar, A., Yadav, V. and Banerjee, D.K. (2025) Green Ammonia: The Future of Clean Energy.
- [14] Kumar, A., Sharma, K., Yadav, V. and Banerjee, D.K. (2025) Hydrogen Horizons: Tech, Trends, and Tomorrow.
- [15] He, T., Liu, X. and Zhao, Y. (2022) Degradation Modeling in Solid Oxide Electrolysis Systems: A Comparative Analysis of Operation Modes. *Journal of Power Sources*, **520**, Article ID: 230802.
- [16] Haynes, W.M. (2014) *CRC Handbook of Chemistry and Physics*. 95th Edition, CRC Press.
- [17] Müller, M., Pfeifer, M., Holtz, D. and Müller, K. (2024) Comparison of Green Ammonia and Green Hydrogen Pathways in Terms of Energy Efficiency. *Fuel*, **357**, Article ID: 129843. <https://doi.org/10.1016/j.fuel.2023.129843>
- [18] Lee, B., Lim, D., Lee, H. and Lim, H. (2021) Which Water Electrolysis Technology Is Appropriate? Critical Insights of Potential Water Electrolysis for Green Ammonia Production. *Renewable and Sustainable Energy Reviews*, **143**, Article ID: 110963.
<https://doi.org/10.1016/j.rser.2021.110963>
- [19] Lee, B., Winter, L.R., Lee, H., Lim, D., Lim, H. and Elimelech, M. (2022) Pathways to a Green Ammonia Future. *ACS Energy Letters*, **7**, 3032-3038.
<https://doi.org/10.1021/acseenergylett.2c01615>