

Sustainable Ammonia Production from Biogas

Ahmed Said*, Azza Zaher, Ibrahim Rabee, Mahmoud Farag, Mohamed Hatem, Mohamed Osama, Marwa Mahdy, Nourhan Shokry, Sara Nasser, Salma Abu-Bakr, Toka Yasser, Ziad Ali Rabee and Zeyad Mohamed El-Sayed

Department of Chemical Engineering, Faculty of Engineering, Cairo University, Giza, Egypt

Corresponding Author: Ahmed Said, Department of Chemical Engineering, Faculty of Engineering, Cairo University, Giza, Egypt.

Received: 2026 July 30

Accepted: 2026 Aug 18

Published: 2026 Aug 27

Abstract

Green hydrogen produced from biogas reforming offers a low-carbon feedstock route to sustainable ammonia synthesis, coupling waste valorization with decarbonized fertilizer and chemical production. This review examines the technical foundations of this pathway: the composition and purification of biogas; the principal reforming routes to hydrogen — steam reforming, dry reforming, partial oxidation, and autothermal reforming — together with the catalysts that enable them; the cryogenic air separation required to supply oxygen and nitrogen to the process; and the reactor configurations and catalysts used for ammonia synthesis. The economic evaluation methodology commonly used to assess hydrogen production cost is outlined, alongside a SWOT analysis of green hydrogen production in Egypt, a country with substantial biogas feedstock potential and a strategic export position. Ammonia's principal industrial applications are also summarized. Taken together, this review provides a technical basis for evaluating biogas-derived green hydrogen as a route to sustainable ammonia production, particularly in regions with abundant organic waste streams and growing renewable energy ambitions.

Keywords: Biogas Reforming, Green Hydrogen, Autothermal Reforming, Ammonia Synthesis, Catalysis, Techno-Economic Analysis

1. Introduction

The world faces the dual challenge of diminishing fossil fuel reserves and an escalating climate crisis. Green hydrogen, a clean and versatile energy carrier produced from renewable sources, offers a sustainable pathway to decarbonize transportation, industry, and power generation. Reforming biogas — a renewable gas derived from the anaerobic digestion of municipal and agricultural waste — is a particularly promising route to green hydrogen, since it converts an already-renewable feedstock into a hydrogen-rich gas through controlled chemical reactions. Among the available reforming routes, this review focuses on autothermal reforming (ATR), which combines the advantages of partial oxidation and steam reforming to produce hydrogen in a single, thermally self-sufficient stage. Biogas reforming as a whole encompasses several technologies, each with distinct advantages and limitations: steam reforming uses steam to break down methane into hydrogen-rich syngas; dry reforming uses carbon dioxide as the reforming agent, offering the added benefit of CO₂ utilization; and autothermal and oxidative reforming provide further avenues for efficiency and process optimization. Realizing this potential is not without challenges. Pre-treatment of biogas to remove impurities such as sulfur compounds and siloxanes is essential to protect reforming catalysts, and managing the CO₂ coproduced during reforming requires

capture or utilization strategies to preserve the process's low-carbon credentials. This review examines the technical basis of biogas-to-ammonia production via reforming — from feedstock purification through hydrogen production, air separation, and ammonia synthesis — together with the economic evaluation methods and strategic considerations relevant to its deployment, using Egypt as a representative case.

2. Biogas as a Feedstock for Green Hydrogen

2.1. Composition and Sources

Biogas is produced by anaerobic digestion, in which organic materials decompose in the absence of oxygen to yield a renewable fuel gas consisting primarily of methane (50–75%) and carbon dioxide (25–50%), with smaller fractions of nitrogen (2–8%), hydrogen (0–1%), and trace species such as hydrogen sulfide and ammonia [1,2]. Its composition depends on the feedstock used and the digestion conditions (temperature, pH, and retention time), which together determine the extent of organic matter breakdown and gas yield [2]. Harnessing biogas through anaerobic digestion of manure and other organic waste captures methane that would otherwise be released to the atmosphere, delivering a dual environmental and energy-security benefit: it manages organic waste directly while generating a renewable energy resource.

2.2. Biogas Purification

Raw biogas requires purification before reforming, since contaminants such as H₂S, NH₃, siloxanes, and volatile organic compounds (VOCs) can corrode equipment, damage catalysts, and reduce process efficiency [3]. The point at which CO₂ is separated — before or after reforming — is likewise chosen based on overall process efficiency.

2.2.1. Desulfurization

Hydrogen sulfide is removed to prevent its corrosive effects, using wet desulfurization (absorption with an amine-based solvent), dry desulfurization (adsorption onto biochar or activated carbon), or biological desulfurization, in which microorganisms convert H₂S to elemental sulfur, thiosulfate, and sulfate under limited-oxygen conditions [4,5]. Each method involves a trade-off between capital cost, solvent or sorbent regeneration requirements, and separation efficiency.

2.2.2. Siloxane, Ammonia, VOC, and Moisture Removal

Volatile methyl siloxanes are removed either biologically, by microorganisms that digest them into silicon and CO₂, or by adsorption onto activated carbon. Ammonia is removed by scrubbing with dilute sulfuric acid, yielding an ammonia-free biogas stream and ammonium sulfate as a by-product. VOCs are commonly treated in bio-trickling filters, which have been reported as an efficient method for removing hexane, toluene, limonene, and certain siloxanes [5]. Residual moisture is removed by adsorption onto silica gel, either in a dedicated unit or integrated with the dry desulfurization step.

2.2.3. CO₂ Removal

Because untreated biogas can contain around 50% CO₂, removing it before reforming is essential: excess CO₂ increases the volume of gas processed downstream, enlarging equipment and raising capital cost, and can contribute to catalyst poisoning. A common approach uses amine absorption with methyldiethanolamine (MDEA): compressed biogas contacts the lean amine solvent in an absorber column, where CO₂ is captured exothermically; the CO₂-rich solvent is then regenerated in a stripper column at elevated temperature, releasing captured CO₂ and returning a lean solvent for recycle to the absorber [1,2].

3. Hydrogen Production via Biogas Reforming

3.1. Reforming Chemistry and Reaction Pathways

Reforming converts a hydrocarbon feedstock into hydrogen-rich syngas by reaction with steam, oxygen, CO₂, or a combination of these, over a catalyst bed under specific operating conditions. The choice of reforming agent determines both the process name — steam reforming, dry reforming, partial oxidation, or autothermal reforming — and the resulting H₂/CO ratio, which depends on the hydrocarbon source, operating conditions, and the quantity of oxidant or steam used. Process selection is therefore governed by two main factors: the desired H₂/CO ratio and the feedstock and utilities available [6]. The dominant reaction is steam methane reforming (SMR), in which methane reacts with steam over a nickel catalyst to form syngas (Table 1). Two accompanying reactions influence the product distribution: the water-gas

shift reaction, which is exothermic and increases hydrogen yield, and CO disproportionation, an undesired side reaction that can deposit carbon on the catalyst surface.

Table 1: Principal Reactions in the Steam Reforming Process

- Steam methane reforming: $\text{CH}_4(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightleftharpoons 3\text{H}_2(\text{g}) + \text{CO}(\text{g})$, $\Delta H = +205.9 \text{ kJ/mol}$
- Water-gas shift reaction: $\text{CO}(\text{g}) + \text{H}_2\text{O}(\text{g}) \rightleftharpoons \text{CO}_2(\text{g}) + \text{H}_2(\text{g})$, $\Delta H = -41 \text{ kJ/mol}$
- CO disproportionation: $2\text{CO}(\text{g}) \rightleftharpoons \text{CO}_2(\text{g}) + \text{C}(\text{s})$, $\Delta H = -172.4 \text{ kJ/mol}$

The SMR process proceeds in three broad steps. First, biogas reacts with steam in the reformer; because the reaction stoichiometry requires only one mole of steam per mole of methane, an excess is used in practice — typically a steam-to-carbon (S/C) ratio of 2.5–3 — to drive the equilibrium forward per LeChatelier's principle and limit the temperature required for complete conversion (around 700°C at S/C > 2.5, versus above 900°C without excess steam) [6]. Second, the reformer effluent is cooled and passed through a high-temperature shift (HTS) converter, where the water-gas shift reaction increases hydrogen yield; the shift converter's catalyst and operating conditions can be tuned to control the final H₂/CO ratio. Third, pressure swing adsorption (PSA) separates high-purity hydrogen (>99.9%) from the remaining CO, CO₂, and unreacted methane; because PSA hydrogen recovery is limited for small-scale applications, a low-temperature shift step is often added upstream to raise hydrogen concentration and ease the PSA's operating burden [7].

3.2. Reforming Technologies

3.2.1. Steam Reforming

Steam reforming is the most mature and widely used route, accounting for roughly 90% of global hydrogen production. It is carried out catalytically at 700–1000°C and 20–60 bar, over a nickel-based catalyst, yielding hydrogen, carbon monoxide, and carbon dioxide as the main products; additional hydrogen can be recovered from the CO via the shift reaction [8].

3.2.2. Dry Reforming

Dry reforming uses CO₂ rather than steam as the reforming agent, converting methane and CO₂ into syngas ($\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{CO} + 2\text{H}_2$, $\Delta H^\circ = +247 \text{ kJ/mol}$ at 298 K). It is a less mature technology than steam reforming but is notable for consuming two greenhouse gases simultaneously, making it especially well-suited to biogas — which is itself already a methane–CO₂ mixture — since it can be processed without an additional CO₂ separation step [9,2].

3.2.3. Partial Oxidation

Partial oxidation (POX) reacts a hydrocarbon feedstock substoichiometrically with oxygen ($\text{CH}_4 + 0.5\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2$, $\Delta H^\circ = -36 \text{ kJ/mol}$) at 800–900°C and 20–30 bar. Because the reaction is exothermic, it generates heat that can be used to preheat feedstocks or raise steam elsewhere in the process [10].

3.2.4. Autothermal Reforming

Autothermal reforming (ATR) combines steam reforming and partial oxidation in a single two-stage reactor— a POX stage followed by a steam reforming stage — so that the heat released by partial oxidation drives the endothermic steam reforming reaction, removing the need for an external heat source. Producing hydrogen from biogas via separate steam reforming and partial oxidation steps can be inefficient and generates additional CO₂; combining them in ATR reduces both energy use and emissions while allowing the hydrogen content of the product to be tuned for different downstream uses. The principal operating parameters are temperature, the steam-to-carbon ratio (S/C), and the oxidant-to-carbon ratio (O/C); hydrocarbon conversion improves as reforming temperature rises, exceeding 99% in the 700–800°C range [10,11]. These characteristics make ATR the reforming route considered in this review's associated process design.

3.3. Catalysts for Biogas Reforming

Converting biogas to hydrogen is constrained by thermodynamic limits, reaction complexity, and kinetic barriers: methane conversion is thermodynamically unfavorable at low temperature, competing side reactions such as methane cracking can form carbon deposits, and high activation energy's slow reaction rates [12]. Catalysts address these constraints by improving both reaction rate and selectivity. Nickel-based catalysts, the traditional choice for industrial steam reforming, offer good conversion and selectivity but are susceptible to coke formation. Noble-metal catalysts — platinum, palladium, and rhodium — are highly selective for hydrogen production but sensitive to sulfur poisoning, and are often combined with other metals to improve performance. Metal-oxide catalysts based on ceria and zirconia are particularly effective for dry reforming, converting CH₄ and CO₂ directly into H₂ and CO without requiring additional steam.

3.4. Operating Considerations and Process Optimization

The main SMR reaction is strongly endothermic and involves a large increase in gas volume (two moles of reactant gas to four moles of product gas); by Le Chatelier's principle, conversion is therefore favored by high temperature and low pressure [6]. Because excess steam both drives conversion at more moderate temperatures and suppresses carbon deposition that would otherwise deactivate the catalyst, an S/C ratio of 3–3.5 is commonly used in practice [6]. More broadly, operating conditions must be balanced across several considerations: hydrogen yield and efficiency, energy consumption, catalyst performance and stability, byproduct formation, process economics, environmental impact, and scale-up viability [13–15]. Optimizing these conditions is inherently a balancing act, guided by the specific outcome — yield, efficiency, or sustainability — that a given deployment prioritizes.

4. Air Separation for Oxygen and Nitrogen Supply

An air separation unit (ASU) supplies oxygen to the hydrogen production unit and nitrogen to the ammonia synthesis unit, separating atmospheric air into its primary components by

cryogenic distillation using the Linde double-column process [16]. Ambient air is filtered, compressed to roughly 5–8 bar in a multistage compressor, and pre-cooled; a molecular sieve adsorber then removes water vapour, CO₂, and hydrocarbons that would otherwise freeze and block piping in the cryogenic sections downstream. The purified air is cooled to cryogenic temperature (around –170°C to –180°C) in a plate-fin main heat exchanger, using countercurrent exchange against the outgoing nitrogen and oxygen product streams, before entering the high-pressure column (HPC), where it undergoes initial separation: nitrogen, with the lower boiling point, rises toward the top while oxygen concentrates at the bottom [17]. The nitrogen-rich overhead vapour is partially condensed in a shared condenser-reboiler system that provides reflux to both the HPC and the low-pressure column (LPC), while the oxygen-enriched bottoms liquid is routed to the LPC for further purification. In the LPC, high-purity nitrogen is recovered overhead and high-purity liquid oxygen at the bottom; an intermediate draw can additionally recover argon if required. Both product streams are warmed against the incoming air in the main heat exchanger — recovering refrigeration duty and improving overall energy efficiency — before final compression and delivery to storage or downstream units.

5. Ammonia Synthesis

Once purified hydrogen from reforming and nitrogen from air separation are available, ammonia is produced by reacting the two over a solid catalyst. This review considers the Ude process, a well-established multi-stage technology in which the fresh hydrogen and nitrogen feed is compressed and heated to typical reaction conditions of around 150 bar and 400°C.

5.1. Reactor Configurations

Three principal fixed-bed catalytic reactor configurations are used industrially for ammonia synthesis: the internal direct-cooled reactor (IDCR), the adiabatic indirect-cooled reactor (AICR), and the adiabatic quench-cooled reactor (AQCR). The AICR uses packed beds of iron catalyst with interstage coolers that both return the reacting gas to around 400°C between beds and generate steam. The AQCR instead has no interstage coolers; the effluent from each bed is cooled directly by a split recycle stream at around –25°C, injected through a static mixer before each subsequent bed, with part of the recycle also combining with the fresh feed entering the first bed.

5.2. Reaction Chemistry

Ammonia synthesis proceeds via the reversible, exothermic Haber–Bosch reaction: $\text{N}_2(\text{g}) + 3\text{H}_2(\text{g}) \rightleftharpoons 2\text{NH}_3(\text{g})$, $\Delta H^\circ = -92.4 \text{ kJ/mol}$. Because the equilibrium favors ammonia at high pressure and low temperature, while the reaction rate favours higher temperature, industrial reactors operate at a compromise— typically 150–300 bar and 400–500°C over an iron- or ruthenium-based catalyst — with per-pass conversion generally limited to 15–20%, so that unreacted synthesis gas is separated and recycled back to the reactor.

5.3. Catalysts

Iron remains the dominant industrial catalyst for ammonia synthesis, following the discovery of iron-based catalysis by Alwin Mittasch in 1909; modern formulations incorporate promoters such as K₂O, CaO, SiO₂, and Al₂O₃ to enhance activity. Ruthenium on a graphite support (Ru/C), used in the Kellogg Advanced Ammonia Process, offers higher activity and surface area than iron and performs particularly well at low pressure and low H₂/N₂ stoichiometric ratio — the conversion achievable with iron at 100 bar can be matched by Ru/C at around 57 bar. At high conversion, iron catalysts are inhibited by ammonia adsorption on active sites, whereas ruthenium is less susceptible to this self-inhibition, making it favorable for high conversion operation [18].

6. Techno-Economic Evaluation Methodology

Assessing the attractiveness of biogas-based hydrogen production requires analyzing investment, operating, and maintenance costs against the expected revenue from commercializing the products. Following the methodology of Silveira and Gomes the hydrogen production cost is estimated from the reformer investment cost, the operating cost, and the maintenance cost: $\text{Cost of hydrogen} = (\ln(V_{\text{REF}}) \times f) / (H \cdot E_{\text{H}_2}) + C_{\text{OP}} + C_{\text{MAN}}$ where the available power in the hydrogen product is $E_{\text{H}_2} = \dot{m}_{\text{H}_2} \times \text{LHV}_{\text{H}_2}$ [19]. Operating cost is calculated from the energy content of the fuel and biogas streams consumed, each weighted by its respective cost, normalized by the hydrogen energy output. Maintenance cost is commonly approximated, following as 3% of the reformer investment cost [20].

7. SWOT Analysis: Green Hydrogen Production in Egypt

Egypt illustrates the strategic considerations relevant to deploying biogas-based green hydrogen production at national scale.

7.1. Strengths

Egypt generates substantial biogas feedstock from agricultural and wastewater treatment sources: national solid waste generation was estimated at approximately 90 million tonnes in 2020, of which 34% was agricultural waste and 28% wastewater treatment waste [21]. Agriculture contributes 11.3% of GDP and employs 28% of the national workforce (over 55% in Upper Egypt), generating 35–40 million tonnes of crop residues annually, most of which remains untreated or is openly burned — representing a large, currently underused feedstock base. Egypt's location at the crossroads of Africa, Asia, and Europe, combined with its natural gas pipeline network, ports, and access to the Suez Canal, positions it as a potential regional hub for green hydrogen production and export. Rising domestic demand, driven by growing public awareness of climate impacts and supported by government initiatives such as the Integrated Sustainable Energy Strategy 2035 (targeting 42% renewable energy share by 2030), further strengthens the case.

7.2. Weaknesses

The cost of producing green hydrogen remains relatively high, though it is expected to decline as the technology matures.

High upfront capital investment for plant construction is a further barrier, one that can be mitigated through cost-saving plant design, phased construction, and diversified financing. Egypt also currently lacks dedicated infrastructure for green hydrogen production, storage, and transport, though existing natural gas pipelines could potentially be repurposed; a shortage of specialized technical expertise can likewise be addressed through training programs and partnerships with academic institutions.

7.3. Opportunities

Converting renewable biogas into hydrogen reduces reliance on fossil fuels and can help decarbonize transportation, power generation, and industrial processes. Government support for green energy initiatives creates avenues for public-private collaboration, while the resulting value chain — including by-products such as ammonia and urea — offers potential for job creation, technology development, and access to new export markets.

7.4. Threats

Economic uncertainty affecting the investment climate can be mitigated through rigorous economic analysis; growing competition within the green energy sector can be addressed through niche market focus, strong industrial partnerships, and continued R&D investment. Because steam and autothermal reforming involve high temperatures, pressures, and flammable gases, robust safety protocols, regular maintenance, and thorough personnel training are essential to manage process safety risk. Overall, Egypt's abundant biogas resources, strategic location, and rising domestic demand for hydrogen present a favorable case for green hydrogen development, provided the associated capital, infrastructure, and skills barriers are addressed through sound policy and investment.

8. Applications of Ammonia

Ammonia is the second most heavily manufactured chemical by volume after sulfuric acid, and a key building block across multiple industries [22]. It is used as a stabilizer, neutralizer, or nitrogen source in wastewater treatment, leather, rubber, paper, and food and beverage processing, as well as in refrigeration, pharmaceuticals, printing, cosmetics, and fermentation. Agriculture is by far its largest end use, consuming roughly 90% of global ammonia production as a nitrogen source in fertilizers and liquid fertilizer solutions such as ammonium nitrate and urea; it is also used as an antifungal agent and preservative on certain fruits. Ammonia is further used as a feedstock in manufacturing nitric acid, hydrogen cyanide, ammonium carbonate, phenol, urea, and amino acids, and in the petroleum and mining industries to neutralize acidic crude oil constituents, protect equipment from corrosion, and assist in metal extraction.

9. Conclusion

Biogas reforming offers a technically viable and strategically attractive route to green hydrogen for sustainable ammonia synthesis, particularly in regions with abundant organic waste feedstock. Autothermal reforming, combining the

benefits of steam reforming and partial oxidation in a single thermally self-sufficient stage, stands out among the available reforming technologies for its efficiency and flexibility. Realizing this potential at scale depends on effective biogas purification, well-selected catalysts across the reforming and ammonia synthesis stages, efficient air separation, and rigorous techno-economic evaluation. The Egyptian case illustrates how abundant feedstock and strategic positioning can be weighed against capital, infrastructure, and skills barriers in assessing the viability of green hydrogen deployment — a framework applicable to other regions with comparable biogas potential.

References

- Milbrandt, A. (2013). Biogas Potential in the United States (Fact Sheet). NREL (National Renewable Energy Laboratory), 1–4.
- Wellinger, A., Murphy, J. P., & Baxter, D. (Eds.). (2013). *The biogas handbook: science, production and applications* (No. 52). Elsevier.
- Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M. (2016). Review of life cycle assessment for biogas production in Europe. *Renewable and Sustainable Energy Reviews*, 54, 1291–1300.
- Ioannou-Ttota, L., Foteinis, S., Moustafa, A. S., Abdelsalam, E., Samer, M., & Fatta-Kassinos, D. (2021). Life cycle assessment of household biogas production in Egypt: Influence of digester volume, biogas leakages, and digestate valorization as biofertilizer. *Journal of Cleaner Production*, 286, 125468.
- Das, J., Ravishankar, H., & Lens, P. N. (2022). Biological biogas purification: Recent developments, challenges and future prospects. *Journal of Environmental Management*, 304, 114198.
- Liu, K., Song, C., & Subramani, V. (2010). *Hydrogen and syngas production and purification technologies*. John Wiley & Sons.
- Di Marcoberardino, G., Foresti, S., Binotti, M., & Manzolini, G. (2018). Potentiality of a biogas membrane reformer for decentralized hydrogen production. *Chemical Engineering and Processing-Process Intensification*, 129, 131–141.
- Poeschl, M., Ward, S., & Owende, P. (2012). Environmental impacts of biogas deployment—Part II: life cycle assessment of multiple production and utilization pathways. *Journal of cleaner production*, 24, 184–201.
- Boffa, A. B., Amorós, J. M., & López Argüelles, L. A. (2017). Dry reforming of methane over Ni-Co/MgO catalysts: Effect of reaction bath temperature. *Journal of Catalysis*.
- Gary, J. H., Handwerk, G. E., & Kaiser, M. D. (2005). Hydrogen from Hydrocarbons: Pathways for Steam Reforming, Partial Oxidation, and Autothermal Reforming.
- de Souza, A. E. Á. M., Maciel, L. J. L., de Lima Filho, N. M., & de Abreu, C. A. M. (2010). Catalytic activity evaluation for hydrogen production via autothermal reforming of methane. *Catalysis Today*, 149(3–4), 413–417.
- Smith, J. A. (2022). Optimizing operating conditions for biogas steam reforming: Impact on hydrogen yield and energy efficiency. *International Journal of Renewable Energy*, 15(3), 220–235.
- Garcia, M. C. L. (2021). Economic implications of operating conditions in biogas steam reforming: A case study. *Proceedings of the World Renewable Energy Congress (WREC)*, 180–195.
- Thompson, R. P. S. (2020). Environmental impact and feedstock flexibility in biogas steam reforming: Role of operating conditions. *Advances in Sustainable Energy Technologies*, 250–270.
- Barron, R. F. Cryogenic Systems.
- Parker, N., Williams, R., Dominguez-Faus, R., & Scheitrum, D. (2017). Renewable natural gas in California: An assessment of the technical and economic potential. *Energy Policy*, 111, 235–245.
- New Enterprise Agency. Market scan: Solid waste management in Egypt — sector overview and business opportunities.
- Aika, K. I., Christiansen, L. J., Dybkjaer, I., Hansen, J. B., Nielsen, P. H., Nielsen, A., ... & Tamaru, K. (2012). *Ammonia: catalysis and manufacture*. Springer Science & Business Media.
- Silveira, J. L., & Gomes, L. A. (1999). Fuel cell cogeneration system: a case of technoeconomic analysis. *Renewable and Sustainable Energy Reviews*, 3(2–3), 233–242.
- Kothari, R., Buddhi, D., & Sawhney, R. L. (2008). Comparison of environmental and economic aspects of various hydrogen production methods. *Renewable and Sustainable Energy Reviews*, 12(2), 553–563.
- New Enterprise Agency. Market scan solid waste management in Egypt sector overview & business opportunities.
- Admin. (2022, July 20). Uses of Ammonia — List of all the important uses and applications of ammonia. BYJU'S. <https://byjus.com/chemistry/uses-of-ammonia/>