

ANNEX 1 (Andrea Perrino Dissertation)

Green ammonia production emerging pathways hold long-term potential for more decentralised and sustainable ammonia production, provided that significant improvements in efficiency, scalability and technological maturity can be achieved (Palhares, Matos and Okigami, 2025). The most relevant emerging pathways include:

- **Direct electrochemical N₂-to-ammonia synthesis**, through the electrochemical nitrogen reduction reaction (eNRR): as a direct alternative to the HB process, electricity is used to directly convert nitrogen (N₂) from the air into ammonia (NH₃) (McPherson et al., 2019) ;
- **Photocatalytic ammonia synthesis (PAS)**, based on the photocatalytic nitrogen reduction reaction (pNRR): this follows a similar principle to eNRR, but uses sunlight instead of electricity to provide the energy needed to convert N₂ into NH₃ (Singh et al., 2023; Zhang et al. 2019);
- **Non-thermal plasma-assisted ammonia synthesis**, based on plasma-driven nitrogen activation: electricity is used to create a plasma that activates nitrogen (N₂), making it more reactive and easier to convert into ammonia. The main difference from eNRR is therefore how the nitrogen is activated (Zhang et al. 2023).
- **Electrochemical ammonia production from nitrate or NO_x**: unlike the previous pathways, this process does not start with N₂ from the air. Instead, it uses nitrogen already present in other forms, such as nitrates in wastewater or NO_x in industrial emissions, and converts it into ammonia using electricity (Cui et al. 2026). This approach can therefore combine waste treatment with ammonia production¹. Pani Clean, an Iowa-based clean-tech company interviewed for this dissertation, combines membrane separation with electrochemical conversion to remove nitrate from contaminated water and convert it into ammonia-based products. As nitrate is more soluble and reactive than N₂, the process both removes a pollutant and generates a valuable product. According to them, this pathway is particularly promising for small- and medium-scale distributed applications, while renewable hydrogen coupled with Haber–Bosch is likely to remain dominant for large-scale commodity production².

¹ This process, also referred to as the nitrate reduction reaction (NO₃⁻RR), differs fundamentally from another pathway under consideration for ammonia decarbonisation: conventional Haber–Bosch synthesis using hydrogen derived from biomass and waste. While nitrate and NO_x reduction pathways modify the nitrogen feedstock by using nitrate (NO₃⁻) or other nitrogen oxides, thereby avoiding the need to activate atmospheric N₂, biomass-based Haber–Bosch synthesis retains the conventional N₂-to-NH₃ conversion route while replacing fossil-derived hydrogen with hydrogen produced from renewable biomass and waste resources.

² Interview with Joun Lee, CEO of Pani Clean, email correspondence, 1 August 2026.

While these alternative decarbonised ammonia synthesis processes hold potential for the future, they currently remain at the R&D level. According to Andersen et al. (2019), the amount of ammonia produced during electrochemical nitrogen fixation experiments is often so small that it is even difficult to determine whether the measured ammonia originates from the reaction itself or from contamination by ammonia present in the surrounding environment.

In fact, all five clean-tech enterprises interviewed agreed that, at present, only the e-HB process is commercially viable for clean ammonia production. This view was shared even by the two companies that had explored alternative pathways. Among them, NitroVolt pursued direct electrochemical ammonia synthesis for decentralised production by farmers but ultimately ceased operations after encountering significant challenges in scaling the model.³

³ Interview with Mattia Saccoccio, CTO and Co-founder of NitroVolt ApS, online, 08 July 2026.