Enabling Green NH_3: A Path to Decentralized Energy Futures

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Ammonia is a key commodity, with annual production reaching approximately 175 million tons. This figure is expected to grow by 3–5% in the coming years, driven by NH_3 emerging role as both H_2 carrier and energy vector. Currently, over 96% of NH_3 is synthesized via the Haber-Bosch process, which relies on fossil fuels to generate H_2 through steam reforming. As a result, ammonia synthesis contributes approximately 1.2% of total global anthropogenic CO_2 emissions, highlighting the urgent need for sustainable alternatives.

Transitioning to green NH_3, produced using H_2 from renewable-powered water electrolysis, is a critical step toward decarbonization. However, conventional large-scale Haber-Bosch plants, designed for continuous, high-load operation, are ill-suited to intermittent renewables. This limitation has driven interest in small-scale, decentralized ammonia plants, which offer operational flexibility and modularity, better aligning with renewable energy dynamics.

Decentralizing production calls for an intensification of the traditional Haber-Bosch configuration. Conventionally, high pressures favour greater ammonia conversion but limit flexibility. Lowering the operating pressure improves adaptability but decreases equilibrium conversion. To compensate this, researchers are exploring improved catalysts and advanced separation methods to enhance yields under milder conditions. As regards separations, condensation becomes ineffective below 50 bar and thus alternative strategies are being explored, such as catalytic membrane reactors, which combine reaction and separation in one unit; adsorption, considering $CaCl_2$ and $MgCl_2$ for selective ammonia capture; absorption, particularly water-based systems once used by BASF.

In this framework, this study explores the integration of water-based NH_3 absorption downstream of the Haber-Bosch reactor for small-scale green ammonia production. After establishing a preliminary process flow diagram and identifying design constraints, the feasibility of the absorption-enhanced Haber-Bosch layout is demonstrated through Aspen Plus® V14 process simulations. Its performance is evaluated from an energy standpoint. Using pinch analysis, optimal stream coupling is achieved to eliminate the need of external hot utilities. NH_3-equivalent metrics shows that a single-stage absorption-enhanced system offers superior thermal and electrical efficiency compared to traditional designs. Further investigations consider two-stage reactor configurations and isothermal absorption scenarios, demonstrating the feasibility of this approach for decentralized, carbon-free ammonia production. These findings pave the way for a decentralized, low-carbon ammonia economy.

Keywords: *process design, renewable energy, decentralized production, Haber-Bosch intensification*