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GREEN AMMONIA PRODUCTION AT SMALL-SCALE

Technological Status and Perspectives for Modular Production Systems

PTX HUB KNOWLEDGE PAPERS

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ABBREVIATIONS

AEL	Alkaline electrolysis
AEM	Anion Exchange Membrane
AIGA	Asian Industrial Gases Association
ASU	Air Separation Unit
ATR	Autothermal Reforming
Bio-Ammonia	Biomass-derived ammonia
CO	Carbon Monoxide
CO_2	Carbon Dioxide
E-Ammonia	Electricity-based (green) ammonia
H_2	Hydrogen
H_2O	Water
Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
MED	Multi-Effect Distillation
MSF	Multi-Stage Flash Desalination
MW	Megawatt
MWh	Megawatt Hour
N_2	Nitrogen
NH_3	Ammonia
Nm^3	Normal Cubic Metre (standardised gas volume)
O_2	Oxygen
PEM	Proton Exchange Membrane (Electrolyser)
POX	Partial Oxidation
PSA	Pressure Swing Adsorption
PV	Photovoltaics
RO	Reverse Osmosis
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
SSAS	Solid-State Ammonia Synthesis
TDS	Total Dissolved Solids
t/day	Tonnes per day
TRL	Technology Readiness Level
UAN	Urea Ammonium Nitrate
WVURC	West Virginia University Research Corporation
°C	Degrees Celsius.

1. Introduction

The defossilisation of industrial processes and the global transition to sustainable energy and raw material cycles require new approaches to the production of basic chemicals. Green ammonia (NH_3), produced from renewable hydrogen (H_2) and atmospheric nitrogen (N_2), offers a promising perspective, both as a CO_2-free energy carrier and as a sustainable feedstock for fertilisers and industrial applications.

To date, large-scale plants (>1000 t NH_3/day) dominate the market. These have been optimised economically and energetically over decades but based on fossil energy carriers. They require extensive infrastructure and centralised production sites. One example is the Donaldsonville Complex operated by CF Industries in Louisiana, USA. Covering an area of approximately 570 hectares along the Mississippi River, the site hosts six large-scale ammonia plants, five urea plants, four nitric acid plants, three urea ammonium nitrate (UAN) plants, and one diesel exhaust fluid plant. The annual production capacity is nearly 8 million metric tonnes of N_2 products for agricultural and industrial uses (CF Industries Holdings, Inc., n.d.). The Ammonia-6 plant at the complex, commissioned in 2016, is considered the world's largest single ammonia production facility (CF Industries Holdings, Inc., 2025). It uses the Haber-Bosch process, which synthesises N_2 from air with H_2 under high pressure and temperature.

Shifting away from fossil energy, the underlying design paradigm for such large-scale facilities may be challenged. In many applications of renewable nature, such as decentralised agriculture, remote industrial sites, or regions with weak grid infrastructure – local, small-scale ammonia production is technically, ecologically, and logistically more appropriate (Tonelli et al., 2024), (Sheran Munasinghe & Krimer, 2024), (Guillermo et al., 2024).

This paper is aimed at engineers, process designers, and decision-makers involved in the planning and implementation of decentralised ammonia production systems. The goal is to provide a structured technical overview of the specific requirements, technologies, and integration aspects relevant to small-scale green ammonia production (1–50 t/day). By comparing large-scale and small-scale system configurations, outlining available process options, and discussing practical implementation challenges, the paper aims to support informed decision-making and facilitate the planning and realisation of future-proof, flexible, and low-carbon ammonia production units.

1.1 Disclaimer - Safety and environmental aspects

While this paper focuses on the technical aspects of small-scale green ammonia production, it is important to emphasise that any ammonia synthesis system, regardless of scale, must be subject to thorough safety and environmental considerations.

Ammonia is a toxic, corrosive and environmentally hazardous substance. Even in small concentrations, it poses serious health risks and can cause significant ecological damage in the event of leaks, especially with respect to soil, groundwater, and aquatic ecosystems.

Therefore, every project involving ammonia production or handling should include:

- a **comprehensive hazard and operability analysis (HAZOP/HAZID)** during the planning phase,
- the implementation of **appropriate safety devices**, such as leak detection, emergency shutdown systems, secondary containment, and ventilation,
- **training of all operational personnel** in safety protocols and emergency response,
- and full compliance with **environmental protection regulations** (e.g., water protection laws, air emission limits, and chemical storage regulations).

This applies equally to modular and containerised small-scale systems, which may be deployed in rural or infrastructure-poor environments. Risk assessments must also account for site-specific conditions, including proximity to groundwater, residential areas, or agricultural use.

This paper focuses on the process and system-level technologies for green ammonia production. Safety assessments, regulatory compliance, and environmental protection measures must be considered separately and are not addressed in detail herein.

2. Matrix: Large-scale vs. small-scale ammonia production

To understand the specific requirements and challenges of small-scale ammonia production, it is useful to first compare it directly with large-scale facilities. The following matrix (Table 1) contrasts key technical, infrastructural, and operational parameters. The goal is to highlight areas where planning approaches, technologies, and operating conditions differ and where similar requirements exist, regardless of plant size.

This structured comparison serves not only as a guide for selecting appropriate components, but also as a decision-making tool for evaluating the fundamental feasibility of a modular plant concept under specific local conditions. It identifies which process steps are particularly critical for successful decentralised implementation (e.g., H_2 production, process integration) and where opportunities exist for simplification or alternative process technologies (e.g., N_2 generation, automation).
Table 1 thus provides the conceptual foundation for the subsequent chapters, which examine each process stage in detail and present suitable technologies for small-scale applications.

Table 1: Comparison of large-scale and small-scale NH_3 synthesis plants (Stefano Mingolla & Rosa, 2025), (Ghavam et al., 2021), (Lee et al., 2022), (Narciso et al., 2025)

Criterion	Large-scale plant (e.g., >1000 t/day)	Small-scale plant (e.g., 1–50 t/day)
Typical Application	Industrial mass production, export	Local supply (e.g., agriculture, mini grids)
Power Demand	>100 MW	1–10 MW
Water Demand (Electrolysis)	~1,5 t H_2O / t NH_3	Linearly scaled; local water treatment required
N_2 Supply	Cryogenic air separation	PSA or membrane technology
Synthesis Process	High-pressure Haber-Bosch (150–300 bar, >450 °C)	Miniaturised HB or alternatives like electrochemical synthesis, plasma based or photocatalytic synthesis
Process Integration	Complex heat recovery	Compact, partially automated
Modularity	Low	High (containerised solutions possible)
NH_3 Transport Requirements	High (centralised distribution)	Low, in case of local consumption
Permitting Effort	Lengthy, site specific	Type specific, plus minor permits via local authorities, partly simplified procedures (varies by region)

3. Fundamental requirements for green ammonia synthesis

The synthesis of ammonia requires fundamentally two inputs: H_2 and Nitrogen (N_2). These must be supplied in the appropriate quality and quantity, regardless of plant size. However, the associated effort to make these available, in terms of both technologies (in part) and system integration, differ significantly between large-scale and small-scale systems (Guillermo et al., 2024). The following sections examine these requirements in the context of small, modular systems (1–50 t NH_3/day) and compare them with the conditions typical of large-scale production.

3.1 Hydrogen production

Large-scale industrial plants
In large-scale industrial ammonia plants, H_2 is currently produced almost exclusively via steam methane reforming (SMR) or autothermal reforming (ATR) of natural gas. While these processes are economically optimised, they cause high CO_2-emissions. The transition to green H_2 is being implemented gradually in some facilities, for example through the integration of multi-megawatt electrolysis clusters (50–200 MW) (Uniper, 2025). A concrete example is the project by BASF in Ludwigshafen (Germany), where a 54 MW proton exchange membrane (PEM) electrolyser was installed in collaboration with Siemens Energy (Figure 1) - currently the largest of its kind in Germany (BASF, 2025). The plant produces up to 8,000 tonnes of green H_2 per year, which is fed into BASF's internal H_2 pipeline network (BASF, 2025). A portion of this green H_2 is used for ammonia production, gradually replacing fossil-based H_2 derived from natural gas.

Figure 1: PEM electrolysis units at the BASF site in Ludwigshafen, Germany (BASF, 2025)

Small-scale plants
Conventional reforming methods are unsuitable for decentralised plants, due to their infrastructure requirements to provide methane (natural gas) as the feedstock. In decentralised setups the limiting element H_2 is well easier supplied via water electrolysis powered by renewable electricity. The electrolysis capacity also follows a new design paradigm, namely the projected demand or production volume in situ. So the electrolysis is directly matched to the wanted NH_3 volume at a given location. The availability of solar or wind power, or even water or air, is usually not a limiting factor in these scenarios.

Due to the usually intermittent nature of locally generated renewable electricity, technology with a high dynamic responsiveness is required. That is especially valid for the electrolysers. PEM systems are best suited for this purpose, as they can respond to changes within seconds and restart without significant degradation (Sayed-Ahmed et al., 2024).

However, alkaline electrolysis (AEL) also remains a technically viable and, in many cases, even operationally preferable option in small-scale systems. While AEL systems have a slower ramp-up time compared to PEM, they are generally more robust, simpler to operate, and less sensitive to impurities in feed water and system fluctuations. In applications where the electrolyser runs for only a few hours per day, such as in solar-dominated systems, the somewhat slower startup of AEL may be acceptable. In return, the reduced complexity and proven long-term durability can be advantageous in remote or low-maintenance environments.

In addition, anion exchange membrane (AEM) electrolysis is a relatively new commercial technology that combines some advantages of both AEL and PEM systems. These include the use of non-noble metals, moderate current densities, and lower materials cost. AEM electrolysers are already available from several suppliers, primarily in the form of modular systems for capacities below 1 MW. While AEM systems currently play a minor role in the market, they show considerable promise for future use in decentralised and small-scale ammonia production, particularly where cost sensitivity and modularity are critical (Carmo et al., 2013), (Götz et al., 2016).

The use of batteries to buffer electricity upstream of electrolysis has also become a viable option, thanks to the global availability of more robust and affordable technologies.

Key requirements for H_2 generation in small, modular systems include (Guillermo et al., 2024), (Sayed-Ahmed et al., 2024), (NEL, 2025), (Carmo et al., 2013), (Götz et al., 2016):

- **Modularity** (scalable output from a few hundred kW up to approx. 20 MW)
- **Dynamic responsiveness** (flexible operation in conjunction with renewable energy or battery storage)
- **Compact space and weight requirements** for single modules to be transportes
- **Simple integration of modules (containerised or skid-based systems)** into a system in situ
- **High degree of automation and remote control**, as operating staff is not available or only for simpler interventions
- **Low maintenance / high robustness**, as maintenence logitics are generally too expensive for small scale plants

For NH_3 production of 10 t/day, approximately 1.8 t of H_2/day is required, equivalent to about 75 kg of H_2 per hour. At a specific electricity consumption of 50–55 kWh/kg H_2, this translates to an electrical connection capacity of roughly 3.5–4.0 MW. Most electrolysers currently available in the small-scale segment offer power outputs between 0.1–5.0 MW per module and can be cascaded.

Stoichiometrically, the electrolysis of water requires approximately 8.9 litres of water per kilogram of H_2 produced. However, the actual water demand is significantly higher when accounting for water used in auxiliary systems (balance of plant), purification, cooling, and humidification. Total water consumption can reach up to 35 kg of water per kg of H_2 produced when desalinated water is used as the source, especially in modular or remote green H_2 systems where water recycling may be limited (Jaeger & Salgado, 2023) .

Table 2 presents the suitability of different electrolysis technologies for H_2 production in large-scale and small-scale systems.

Table 2: Comparison of electrolysis processes according to system size (Sayed-Ahmed et al., 2024), (Götz et al., 2016)

Electrolysis technology	Large-scale Plants (>20 MW)	Small-scale Plants (100 kW–10 MW)
Alkaline (AEL)	Proven, cost-effective, suitable for large-scale systems	Technically feasible, but space-intensive
PEM	Increasingly used industrially (e.g., 20–100 MW)	Preferred due to modularity and dynamic response
Solid oxide electrolyser cell (SOEC)	Pilot projects, high efficiency	Currently not viable for small-scale applications
AEM (early commercial)	Not yet used at industrial scale	Technically promising; early commercial application

Comparison of requirements: Large-scale vs. small-scale plants

Depending on the plant size, H_2 production involves different priorities and requirements, both in terms of technological configuration and infrastructure integration. In large-scale industrial plants, H_2 is typically produced centrally and continuously, still predominantly via SMR, or (during initial transitions) through very large electrolysis systems with capacities of 20 MW and more. These systems are designed for continuous operation, often grid-connected, and embedded in complex chemical park infrastructures with well-developed water, energy, and gas networks (Mößle et al., 2024). Supply security is of utmost importance, as production interruptions can result in significant economic losses.

In contrast, small-scale modular plants are characterised by distinct operational and infrastructural requirements. Here, H_2 production is decentralised, flexible, and typically based on PEM electrolysis. System capacities usually range between 500 kW and 10 MW, enabling a much more compact design, often in the form of containerised units. This modularity allows for rapid deployment, even in remote or infrastructure-poor locations. Operation is often in partial load, adjusted to the fluctuating availability of renewable energy (e.g., from PV or wind), which demands a high level of controllability from the electrolysers (Lafoyiannis et al., 2024).

There are also clear differences in maintenance and staffing: while large-scale facilities are continuously monitored by qualified personnel, small-scale systems rely on a high degree of automation, remote monitoring, and low-maintenance operation to ensure reliable performance even in regions without permanent on-site supervision (AIGA, 2023), (ENAPTER, 2023).

Overall, it becomes evident that small-scale plants are not merely 'downsized versions' of large-scale systems, they require distinct solutions in engineering, infrastructure, operation, maintenance, and staffing in many respects.

3.2 Water supply

Water is an essential raw material for electrolysis and thus for the production of green ammonia. Producing one kilogram of H_2 requires approximately 8.92 litres of demineralised water (Hydrogen Europe, 2020).

Large-scale facilities, such as the ammonia plant in Donaldsonville (USA) or the NEOM Green H_2 Project in Saudi Arabia, operate their own water treatment units or are connected to centralised industrial water supply systems (CF Industries Holdings, Inc., n.d.), (Aquatech, 2020). These plants typically utilise surface water (e.g., from rivers or lakes), which is treated in multiple stages, including coarse filtration, precipitation, softening, and deionisation. In water-scarce regions or near coastal areas, seawater desalination is employed. Three technologies are commonly used for this purpose (Table 3):

Table 3: Comparison of seawater desalination technologies (Panagopoulos et al., 2019), (El-Ghonemy, 2018), (Kim et al., 2019)

Technology	Principle	Suitability for large-scale plants
MSF (Multi-Stage Flash)	Thermal evaporation in multiple stages	Very suitable; high energy demand, highly scalable
MED (Multi-Effect Distillation)	Stage-wise distillation with heat recovery	Suitable; more efficient than MSF at moderate throughput
RO (Reverse Osmosis)	Membrane-based, pressure-driven process	Suitable for medium capacities; lower energy consumption

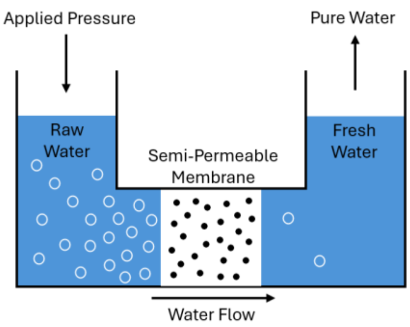
Small-scale plants

Small-scale ammonia plants are often planned for remote regions without access to centralised water infrastructure, such as agricultural operations, mini-grids, or off-grid industrial clusters. As a result, they must rely on compact and flexible water supply systems, depending on local water availability.

Various water sources may be suitable depending on the location. In some regions, groundwater is available, though its use often requires extensive pretreatment. Raw groundwater typically contains iron, manganese, hardness-forming minerals, or microorganisms that must be removed before further processing (Ellis et al., 2000). When surface water (such as from lakes or rivers) is used, sedimentation and biological pre-filtration are necessary to reduce particulate matter and organic contaminants (Panagopoulos et al., 2019). In arid or coastal areas, seawater or brackish water is increasingly used, which in turn requires efficient desalination systems.

The preferred desalination technology for small-scale applications is RO, in which pressurised raw water is forced through a semi-permeable membrane (Leong et al., 2021). Dissolved substances are retained, allowing purified water (fresh water) to pass through (Figure 2).

Figure 2: Simplified illustration of the operating principle of reverse osmosis. Based on (Godfrey, 2022)



Compared to thermal processes such as MSF or MED, which are primarily used in large-scale facilities, RO is significantly more compact, energy-efficient, and available as modular systems (Leong et al., 2021). Manufacturers offer standardised RO units with capacities ranging from 1 to 10 cubic metres per hour, well-suited to the water requirements of decentralised NH_3 plants.

The selection of an appropriate desalination technology fundamentally depends on several factors, including raw water quality, the required purity level, specific energy consumption, and overall economic conditions (Jamaly et al., 2014). RO systems have a technical limitation in terms of raw water salinity: the so-called "burst pressure" limit is typically around 60,000 mg/L of total dissolved solids (TDS) (Ahmad et al., 2020). Beyond this threshold, membrane-based systems become unreliable or economically unfeasible due to mechanical stress. In such cases, thermal desalination technologies like MSF or MED are preferred for large-scale applications, as they are more tolerant of high salinity levels (Jiménez et al., 2018).

Other physical and chemical challenges, such as membrane fouling or elevated raw water temperatures, can also define the operational limits of membrane-based systems under extreme conditions. Nevertheless, when water quality is suitable, RO offers numerous advantages for small-scale applications: high retention rates and water recovery, excellent scalability, low chemical consumption, and easy integration into modular system designs (Leong et al., 2021), (Van Gauwbergen & Baeyens, 1998).

Following desalination, a further purification step is usually required to produce high-purity water, for instance, through ion exchange or electrodeionisation (EDI), to meet the conductivity and purity standards needed for PEM electrolysis (Leong et al., 2021).

Another important aspect is the treatment of wastewater generated throughout the plant. This includes not only the byproducts of electrolysis itself but also water used for pipe flushing, cooling systems, and cleaning processes. As centralised wastewater infrastructure is often unavailable at small-scale sites, compact water treatment systems are used. These typically consist of multi-stage filtration units with activated carbon, sediment separation, and, in some cases, UV disinfection (Ahmad et al., 2020). Recycling the treated water back into the process, for example, for cooling or as feedwater for electrolysis, is often essential, both for environmental reasons and due to limited local water availability.

Therefore, in the planning of modular ammonia plants, water supply should not be seen as a secondary consideration but as an integral component of the overall system. It directly affects the technical design of the electrolyser, the required footprint, energy consumption, and the long-term operational reliability of the plant. Depending on site-specific conditions, it may be advantageous to integrate water treatment, desalination, and wastewater management into a single container or module, to simplify transport, installation, and operation (Fluence, n.d.).

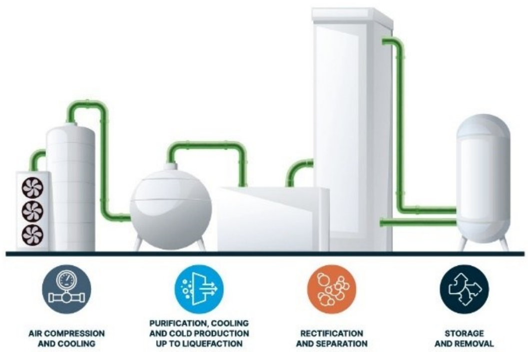
3.3 Nitrogen production

In addition to H_2, N_2 is the second essential feedstock for ammonia synthesis. In both large- and small-scale plants, N_2 is extracted from ambient air, which consists of approximately 78% N_2 by volume. The key challenge lies in separating N_2 from oxygen, argon, CO_2, and moisture to provide a N_2 stream that is as pure and dry as possible for the synthesis process. While large-scale industrial plants rely on proven, high-purity separation technologies, small-scale systems must prioritise compactness, energy efficiency, and ease of integration.

Large-scale industrial plants

In large-scale industrial ammonia plants, N_2 is typically produced via cryogenic air separation (**ASU – Air Separation Unit**). In this process, ambient air is first compressed and purified of water, CO_2, and dust particles, then liquefied through a multi-stage cooling cycle (Chemical Engineering World, 2020), (Jiang & Feng, 2019). As the components of air condense at different temperatures, high-purity streams of N_2, oxygen, and noble gases can be separated (Figure 3).

Figure 3: Process stages involved in air separation (HEROSE, 2024)



This technology provides N_2 at very high purities (>99.999%) and typically at flow rates of several thousand normal cubic metres per hour (Rinker, 2024). However, cryogenic air separation is both energy- and capital-intensive and requires continuous operation (Rinker, 2024). It is therefore economically viable almost exclusively for large-scale plants, not least because the byproduct oxygen can be utilised elsewhere, for example in refineries or nitric acid production.

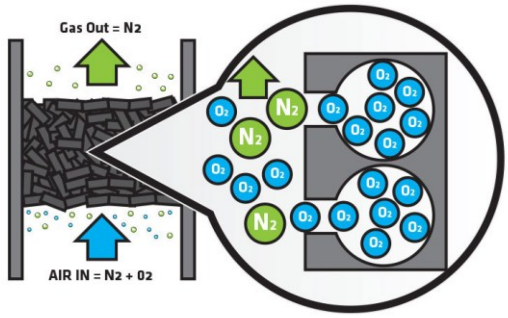
Small-scale plants

Cryogenic air separation is unsuitable for small-scale ammonia plants for several reasons: it is too large, too expensive, infrastructure-intensive, and designed for continuous operation (Rinker, 2024). Instead, more compact technologies are used that allow for economically and energetically viable N_2 supply in the range of a few to several hundred normal cubic metres per hour.

In practice, two technologies have proven particularly effective: **Pressure Swing Adsorption (PSA)** and **membrane separation**.

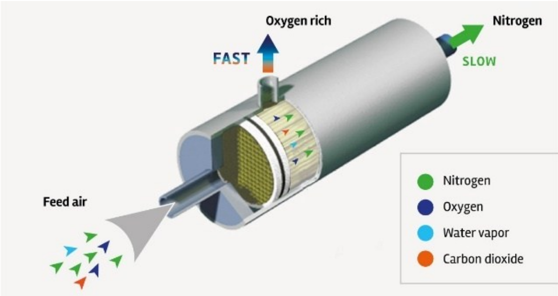
In the **pressure swing adsorption process**, ambient air is treated using an adsorptive method in which specific molecules (primarily oxygen) are captured by a solid adsorbent material, such as a molecular sieve. By cyclically alternating between pressurisation and depressurisation, oxygen is adsorbed and then desorbed, while N_2 can be continuously extracted (Figure 4) (Rinker, 2024), (Dobreva, 2018). PSA systems typically achieve N_2 purities ranging from 95% to 99.999% and are fully automatable (Rinker, 2024). They are robust, low-maintenance, quick to start up, and compact, offering multiple advantages in isolated or decentralised production environments, making them ideally suited for modular NH_3 systems (Bañares-Alcántara et al., 2015).

Figure 4: PSA principle usind Carbon Molecular Sieve (CMS) adsorbent (Dobreva, 2018)



As an alternative, **membrane separation** can be used. This method employs hollow fiber membranes through which pressurised ambient air is passed. Due to differences in diffusion rates, N_2 and oxygen accumulate at different concentrations on opposite sides of the membrane (Figure 5) (Rinker, 2024). Membrane systems are more compact and require less maintenance than PSA systems but generally deliver lower N_2 purities, typically in the range of 95% to 99.5% (Rinker, 2024). For basic applications or when combined with downstream purification stages, they may still be sufficient, particularly in very small-scale plants

Figure 5: Simplified illustration of N_2 generation using membrane technology (Sinergia, 2021)



Comparison of requirements: Large-scale vs. small-scale plants

The choice of an appropriate process depends on several factors: the required N_2 purity, available space, energy efficiency, and maintenance requirements. PSA systems offer the best overall compromise for medium-sized modular plants (e.g., 5–50 t NH_3/day), while membrane-based solutions can be advantageous for very small, self-contained systems (e.g., 1–5 t/day) due to their simplicity (Ai et al., 2022), (Ismail, 2016).

In large-scale plants, air separation is a central component of overall process integration and typically provides both N_2 and process oxygen for additional chemical steps. The high energy efficiency of such systems results from continuous operation, heat recovery, and economies of scale (Rinker, 2024). In contrast, N_2 generation in small-scale plants must be decentralised, flexible, and as low-maintenance as possible. The N_2 produced is used exclusively for ammonia synthesis, and there is typically no intended use for the oxygen byproduct. As a result, the process does not need to accommodate co-product utilisation but should instead be compact and reliable. For a 10 ton NH_3/day plant, the typical N_2 requirement is around 8,000–9,000 Nm^3/day, a quantity that can be readily supplied by a medium-sized PSA system (Amherst & Morgan, 2013).

3.4 Power supply & energy integration

Electric power supply is a key factor in the production of green ammonia. The largest share of electricity consumption is attributed to electrolytic H_2 production, which can account for approximately 70–85% of the total energy demand, especially in small-scale, modular systems without extensive heat recovery or grid buffering (Oxford Institute for Energy Studies, 2024), (Saygin et al., 2023). Other electrical loads include air separation (e.g., PSA), compression, reactor cooling, and process automation. For efficient and stable operation, the entire system (including energy storage) must be tailored to the specific characteristics of the available power source.

Large-scale industrial plants

In large-scale ammonia plants, power is typically supplied via stable grid connections or large-scale renewable energy capacities combined with energy storage systems that provide high baseload capability. Projects such as NEOM in Saudi Arabia (2 GW of electrolysis capacity powered by wind and solar energy) and Iberdrola/Fertiberia in Spain (20 MW of electrolysis, 100 MW of PV) are designed for continuous operation and benefit from synergies through large-scale integration and heat recovery (Atchison, 2022), (Fertiberia, 2024). The continuous power supply enables optimisation of operating points while minimizing storage requirements. In such systems, the specific electricity consumption typically ranges from 11 to 13 MWh per ton of NH_3, with electrolysis alone accounting for approximately 9 to 10 MWh (Wang et al., 2023).

Small-scale plants

For small-scale modular ammonia plants (particularly those in the range of 1–50 t NH_3/day) electricity supply represents a key design factor due to the intermittency. These systems are often planned for regions without stable grid access and are powered directly by renewable energy sources such as PV or wind. The resulting power fluctuations require either electricity-driven operation, where electrolysis and synthesis are adjusted based on energy availability, or a combination with energy storage systems (upstream of the electrolysis), such as battery storage or buffered H_2 tanks (Guillermo et al., 2024) (downstream of the electrolysis).

In decentralised systems, power integration must be understood as a holistic energy management challenge. A critical factor is aligning the dynamic power input with the partial-load capability of the electrolysers (e.g., PEM technology) and developing an effective storage strategy for H_2, N_2, and, if applicable, electricity. A common operational mode involves running the electrolyser during daylight hours (using PV electricity), while the reactor is supplied continuously, e.g. with gases stored during the day for night operation. Alternatively, fully modular operation strategies can be implemented, in which all subsystems are operated or shut down synchronously. This, however, imposes higher demands on automation and material durability (Bañares-Alcántara et al., 2015), (Rouwenhorst, Van der Ham, et al., 2019).

Compared to large-scale facilities, small plants exhibit a higher relative share of energy consumption by auxiliary systems such as cooling, compression, and control. Studies show that in such modular setups, electrolysis accounts for 75–85% of total electricity consumption (Guillermo et al., 2024), (Oxford Institute for Energy Studies, 2024). These figures are particularly relevant when power is supplied intermittently from renewable sources and continuous process integration is not feasible.

An illustrative example of intelligent power integration in a small-scale modular ammonia plant is the *TalusOne* project by Talus Renewables in Kenya. Located at the site of the Kenya Nut Company in Naivasha, the plant produces around 1 ton of green ammonia per day, which is used entirely on-site as fertiliser (TalusAg, 2025). The entire power supply is provided by a 2.1 MW PV system, which is subject to the typical challenges of fluctuating renewable energy input. To stabilise operation of the electrolyser and downstream ammonia synthesis despite daily solar variability, the system is supported by a stationary battery storage unit. This storage smooths the power supply, bridges shortfalls due to cloud cover, and enables consistent energy delivery to the production chain, even during periods of reduced PV output. The combination of solar power and battery storage thus ensures that the plant operates autonomously and independently of the grid, with stable operation of key components and without frequent cycling.

4. Process engineering options for small-scale ammonia synthesis

The growing availability of low-cost renewable energy generation is opening new opportunities for decentralised, small-scale, and modular production. In the range of 1–50 t NH_3 per day, alternative technologies must be evaluated with regard to energy efficiency, operating pressure and temperature, as well as integration into local energy and resource conditions.

4.2 Renewable ammonia production

The defossilisation of ammonia production focuses on replacing emission-intensive H_2 generation with sustainable alternatives. Green ammonia pathways avoid the use of fossil fuels and rely on renewable energy sources or feedstocks.

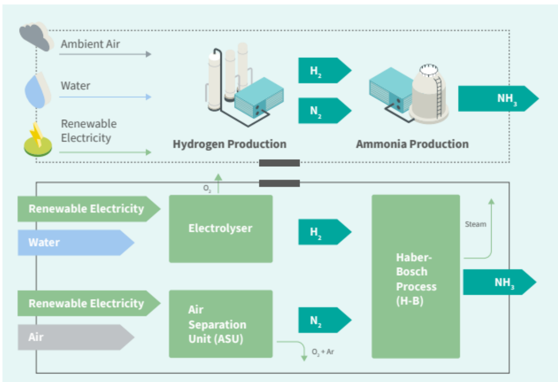
- **E-ammonia**: Utilises renewable electricity to produce H_2 via water electrolysis, which is then combined with N_2 to synthesise ammonia with net-zero emissions.
- **Bio-ammonia**: Uses renewable feedstocks such as biomass or waste materials to generate H_2. Even if these pathways might be net zero, it still causes emissions locally.

Innovative approaches are being developed, including alternative catalytic and electrochemical methods, aimed at further improving efficiency and sustainability.

E-Ammonia

In electricity-based ammonia production (Figure 6), water is split into its components H_2 and O_2 via electrolysis to generate the required H_2 (see Chapter 3.1). N_2, the second element needed for ammonia synthesis, is conventionally extracted from air using the methods described in Chapter 3.3.

Figure 6: Schematic representation of renewable ammonia production via electrolysis. Based on (International PtX Hub, 2025)



This setup aligns with the growing interest in decentralised and modular ammonia production. Such systems offer several advantages: they can be built in close proximity to renewable energy sources and end users, thereby reducing transportation costs and associated emissions. Furthermore, they support regional energy independence and enable flexible scaling according to local demand. The approach is particularly suitable for renewable energy hubs and regions rich in local resources, thus promoting more sustainable and adaptable pathways for ammonia production.

Challenges and pathways for small-scale implementation

Implementing the Haber-Bosch process in decentralised, small-scale ammonia plants with capacities below 50 tonnes per day requires careful adaptation to specific technical, energetic, and operational conditions. In traditional large-scale facilities, efficiency gains are primarily achieved through economies of scale, continuous operation, and comprehensive heat recovery (Anwar et al., 2024). These effects are far less pronounced at smaller scales, necessitating alternative technological solutions and system concepts to ensure stable and economically viable operation.

A key challenge in downsizing lies in the **high relative heat losses**. Due to the unfavourable surface-to-volume ratio of small reactors, a significant portion of the reaction heat is lost to the environment. While large plants efficiently recover this heat for feedstock preheating or steam generation, small systems often lack the structural and economic capacity for such feedback loops. Rouwenhorst et al. demonstrate that, without heat recovery, specific energy consumption can exceed 10 kWh/kg NH_3 (Rouwenhorst, Van der Ham, et al., 2019). As a result, increasing attention is being paid to the development of milder process conditions that better align with intermittent renewable energy and can be operated more efficiently in smaller reactors (Guillermo et al., 2024), (Bañares-Alcántara et al., 2015). Notable progress has been made through the integration of **absorption and adsorption systems**, which enable selective ammonia separation from the reaction mixture, thereby allowing operation at significantly lower temperatures and pressures (Guillermo et al., 2024), (Bañares-Alcántara et al., 2015), (IRENA, 2022). Promising sorbents include metal halides (absorption), zeolites (adsorption), and activated carbons, all of which are thermally and chemically stable (Rouwenhorst, Van der Ham, et al., 2019).

A second limiting factor is the **disproportionately high energy demand for gas compression**, which leads to significantly higher specific operating costs in small plants. While large-scale facilities use multi-stage compressors with high efficiency that amortise over large volume flows, small plants lack these scale advantages. Simulations of a 1.5 kg/h reactor showed that up to 3.6 kWh/kg NH_3 may be required for compression and gas circulation in the reactor loop (Rouwenhorst, Van der Ham, et al., 2019). A promising approach, therefore, is the combination of **sorbent-assisted synthesis at mild conditions** (e.g., 10–30 bar and 200–350 °C) with in-situ ammonia separation. This operating mode eliminates the need for high-pressure compression, reduces heat exchanger requirements, and could ultimately enable integration of reaction and separation in a single reactor vessel (Rouwenhorst, Van der Ham, et al., 2019), (Meers et al., 2020).

A third important challenge is the **limited load flexibility** of conventional Haber-Bosch reactors. The process is optimised for continuous operation under steady-state conditions and responds poorly to fluctuations in temperature, pressure, or feed composition. This conflicts with the operational reality of modular systems, which are often powered by intermittent energy sources such as PV or wind. Research has explored various strategies to increase flexibility. One particularly relevant approach is **"inert variation"**, in which the reaction rate is deliberately reduced by increasing the share of inert gases (e.g., argon) in the feed mixture, without changing the system pressure (Rouwenhorst, Van der Ham, et al., 2019). This enables partial-load operation better suited to fluctuating power input.

Additionally, small-scale systems require a **higher degree of automation and control**, since continuous manual operation, as in large plants, is not economically feasible. Process control must be reliable, low-maintenance, and remotely monitorable. Rouwenhorst et al. emphasise that the success of small-scale NH_3 plants strongly depends on the modularisation and segmentation of the overall system (Rouwenhorst, Van der Ham, et al., 2019). By dividing the plant into semi-autonomous functional units, for example, for

electrolysis, N_2 generation, ammonia synthesis, and separation, sequential or selective operation becomes possible. This not only accommodates intermittent energy supply but also offers advantages in terms of safety and control.
Finally, modular systems often benefit from **regulatory advantages**: facilities below certain thresholds (e.g., <50 t NH_3/day) are not classified as industrial-scale operations in many regions, which reduces permitting requirements (IRENA, 2022), (Fecke et al., 2025). This makes deployment on farms, in off-grid settlements, or in decentralised industrial parks both technically and legally attractive.

In summary, the successful miniaturisation of Haber-Bosch ammonia synthesis requires a combination of process and system-level adaptations. The shift to milder conditions, combined with sorption-assisted separation and flexible control strategies, forms the basis for technically and energetically viable solutions at the decentralised scale.

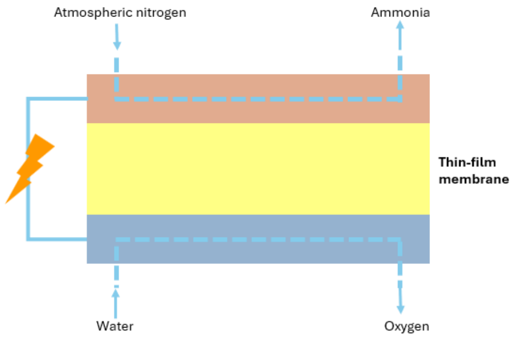
4.3 Alternative concepts for small-scale ammonia synthesis

While the concepts discussed thus far for decentralised ammonia synthesis are based on a two-step approach – first, H_2 and N_2 are produced, followed by their conversion to ammonia via the Haber-Bosch process – there are interesting upcoming alternatives for small, modular systems and fluctuating renewable power supply. These technologies are currently still in research or pilot stage, but the long-term potential is promising.

Direct electrochemical ammonia synthesis (e-Ammonia electrolyser)

Electrochemical ammonia synthesis enables the direct production of NH_3 from air and water using electrical energy, without the need for upstream H_2 generation. The process involves water oxidation at the anode, proton transport through a liquid or solid electrolyte membrane, and N_2 reduction at the cathode (Figure 7). The type of electrolyte used plays a key role in determining the conductivity, stability, and overall efficiency of the process (Heberl, 2017), (Giddey et al., 2013).

Figure 7: Simplified illustration of electrochemical ammonia synthesis. Based on (Campfire, 2024)



One example of this approach is the *CAMPFIRE* technology, which utilises solid-state ammonia synthesis (SSAS) (Campfire, 2024). In this process, water and air serve as feedstocks. Water is split into protons and electrons, with the protons transported through a proton-conducting ceramic thin-film membrane to the cathode, where they react with N_2 to form ammonia (Heberl, 2017). This method eliminates the need for an intermediate H_2 buffer, thereby reducing system complexity and conversion losses.

Despite growing research efforts, electrochemical ammonia synthesis still suffers from low Faradaic efficiency. While its energy consumption is approximately 20% lower than that of coal-based Haber-Bosch processes, it remains about 30% higher than that of natural gas-based plants (Heberl, 2017), (Giddey et al., 2013). Nevertheless, due to its modular design and ability to operate at low temperatures and pressures, the technology is particularly well-suited for integration with intermittent renewable energy sources (Heberl, 2017), (Giddey et al., 2013).

Another major advantage is its potential for decentralised deployment. The low dependency on infrastructure makes this process attractive for off-grid locations, agricultural operations, or micro-industrial applications (Heberl, 2017), (Xu et al., 2009). As such, the technology is especially promising in regions where renewable energy is available but traditional industrial infrastructure is lacking (Shipman & Symes, 2017).

Non-thermal plasma processes (NTP – e-Ammonia)

Plasma-based methods for N_2 fixation were investigated as early as the beginning of the 20th century (e.g., the Birkeland–Eyde process), but recent advances in catalysis and reactor design have renewed interest in this approach. Plasmas, consisting of ionised gases,

radicals, and activated molecules, enable the activation of N_2 through electronic and vibrational excitation (Giddey et al., 2013), (Amar et al., 2011), (Bogaerts & Neyts, 2018), significantly lowering the activation energy required for reaction with H_2 (Giddey et al., 2013), (Mehta et al., 2018), (Hansen et al., 1992).
Combining plasma with heterogeneous catalysts improves selectivity and reduces reverse reactions (Giddey et al., 2013), (Song et al., 2018), (Mehta et al., 2019). For instance, Peng et al. demonstrated that ammonia can be synthesised under mild conditions (50 °C, 1 atm). While conversion rates remain low and reverse reactions occur, the low capital cost, continuous operation under ambient conditions, and suitability for decentralised applications make the approach promising (Shipman & Symes, 2017), (Rouwenhorst, Kim, et al., 2019).

A particularly innovative system has been developed by the West Virginia University Research Corporation (WVURC), where microwave plasma is used to selectively heat only the catalyst, while the surrounding reactor environment remains cool. This localised heating enables high temperatures with high energy efficiency. According to WVURC, the system achieves up to five times the production rate of conventional Haber-Bosch systems (Shipman & Symes, 2017).

The rapid start-up and shutdown capability of plasma-based systems makes them especially suitable for operation with intermittent power sources such as wind or PV. However, the specific energy consumption is still relatively high (Giddey et al., 2013), and further advances in reactor design and catalyst development are necessary to improve the technology readiness level (Peng et al., 2018).

Photocatalytic ammonia synthesis

Another alternative pathway is the photochemical reduction of N_2 to NH_3, which can be driven directly by sunlight. In this process, photons are absorbed by a semiconductor catalyst, promoting electrons to the conduction band and creating holes in the valence band. The excited electrons reduce N_2, while the holes oxidise water, resulting in the formation of ammonia (Carreon, 2019), (Hui et al., 2022).

The efficiency of this process strongly depends on the choice of photocatalyst. Inorganic materials, such as TiO_2-based systems, metal sulfides, and carbon-based compounds, currently demonstrate the most promising performance. Key criteria include a suitable band structure, stability, high N_2 activation capability, and suppression of competing H_2 formation (Klaas et al., 2021). At present, the technology readiness level (TRL) of these methods remains low (TRL ~1), as N_2 activation kinetics at ambient temperature are extremely slow and yields are too low for practical applications (Klaas et al., 2021), (Zhang et al., 2019).

Nevertheless, significant progress has been made through the development of new materials, particularly in the field of photoelectrocatalytic systems. Additionally, there are numerous synergies with other applications of photocatalysis, which could simplify future scale-up. Small-scale applications, such as for greenhouses or agricultural microplants, are already considered feasible (Zhang et al., 2019)

4.4 Evaluation and comparison of small-scale ammonia synthesis options

The preceding sections have demonstrated that small-scale ammonia synthesis differs fundamentally from large-scale implementation, not only in terms of physical boundary conditions but also with regard to system integration, load behaviour, and economies of scale. A well-informed selection of a suitable synthesis method must take into account several criteria, including:

- Reaction temperature and pressure
- Energy efficiency
- Technology readiness level (TRL)
- Modularity
- Load flexibility
- Suitability for fluctuating power supply
- Process complexity and automation potential

At present, the **miniaturised Haber-Bosch process** remains the only commercially available solution for decentralised ammonia production at scales up to 50 t/day. It is technologically mature and reliable, but requires high pressures and temperatures as well as a continuous power supply, which limits its compatibility with fluctuating renewable sources.

Absorption-assisted processes represent an attractive bridge between classical and modular technologies. By integrating adsorption or absorption steps, operating conditions can be shifted, enabling lower pressures, improved energy efficiency, and potential load flexibility. These systems are currently at the pilot stage but offer promising medium-term prospects for modular setups powered by intermittent energy sources (Rouwenhorst, Van der Ham, et al., 2019).

Electrochemical ammonia synthesis is conceptually very appealing for decentralised applications. It operates at ambient temperature and pressure, allows for compact, modular design, and responds well to variable energy input. However, low efficiency and limited long-term stability currently restrict its practical use. In the future, though, it may play a key role, especially in off-grid environments (Rouwenhorst, Van der Ham, et al., 2019), (Heberl, 2017), (Shipman & Symes, 2017).

Plasma-based processes are characterised by a high degree of operational flexibility. They can be operated at low temperatures and pressures and are well-suited for rapid start-up and shutdown. However, their energy efficiency remains low, making them currently suitable only as complementary technologies or for specialised applications (Rouwenhorst, Van der Ham, et al., 2019), (Giddey et al., 2013), (Shipman & Symes, 2017).

Photocatalytic processes are still in the very early stages of development. Despite their conceptual appeal, direct utilisation of sunlight without an intermediate electrical step, their conversion rates and the technical control of the reaction are not yet sufficient for practical deployment. For the foreseeable future, these technologies will remain limited to research and niche applications (Klaas et al., 2021), (Zhang et al., 2019).

Table 4 summarises the key characteristics of the discussed processes:

Table 4: Technological comparison of small-scalle ammonia synthesis processes

Synthesis Process	Temp. [°C]	Pressure [bar]	Specific energy demand [kWh/kg NH_3]	Flexibility	TRL	Suitability for small-scale systems
Miniaturised Haber-Bosch	400–500	80-150	8-12	low	9	Established, robust, limited dynamic operation
Low-P / Absorption-Assisted HB	300–400	10-30	0,7-3,1	medium	4-6	Good option when coupled with renewable energy
Electrochemical synthesis	25–150	1-10	9-15	high	3-4	Highly modular, small footprint
Plasma-based	25–200	1	>15	high	2-4	Compact design, excellent start-stop capability
Photocatalytic	<50	1	Very high (low yield)	high	1-2	Only suitable for niche or research applications

5. Storage of ammonia in decentralised systems

In any ammonia production system, the storage of the final product is a critical interface between synthesis and downstream use. While large-scale ammonia plants typically operate continuously and employ extensive cryogenic or pressurised storage infrastructure, decentralised small-scale plants must address this task under entirely different conditions: limited space, intermittent production, lower volumes, and often limited on-site infrastructure.

Despite these limitations, ammonia storage benefits from over a century of technological maturity. Extensive experience and infrastructure already exist for handling, storing, and transporting anhydrous ammonia, which can facilitate early deployment of decentralised green ammonia systems even before fully new supply chains are built out (Rouwenhorst et al., 2019).

5.1 Storage technologies

Several established and emerging options exist for storing ammonia:

Pressurised storage (ambient temperature, 10–30 bar):
This method uses spherical or cylindrical steel vessels with volumes ranging from 150 to 1,500 tonnes. It is most common in small- to mid-scale plants and serves well as a buffer between the synthesis loop and downstream consumers. Such systems are compact, technically simple, and cost-effective for daily or weekly storage (Humphreys, 2020).

Semi-refrigerated storage (~0 °C):
Used for quantities up to ~3,000 tonnes, this method involves compressing and liquefying ammonia vapors with water-cooled systems in insulated vessels. It is less complex than fully refrigerated storage and comparatively inexpensive (IRENA & AEA, 2022).

Fully refrigerated (cryogenic) storage (−33 °C, atmospheric pressure):
Suitable for large-scale long-term storage (~50,000 tonnes per tank), it is rarely implemented in decentralised contexts due to complexity and energy demand. Risks include impurity buildup (e.g., N_2, H_2) and stress corrosion cracking (Brown, 2018).

Solid-state storage (emerging):
For truly modular systems, solid-state storage using materials such as metal hydrides, amides, or borohydrides is being explored. These systems are inherently safer—reducing risks of leakage and toxic exposure—but remain in early research and are not yet commercially viable (Zhang et al., 2018).

Some large-scale concepts also consider underground or cavern storage (as used in LPG applications), but geological and purity challenges typically rule this out for ammonia (Brown, 2018).

5.2 Storage in small-scale systems

In modular or containerised green ammonia plants (1–50 t NH_3/day), pressurised storage is the preferred method due to its modularity, safety, and commercial availability. Suppliers offer tank systems in the 1–10 m^3 range, ideal for balancing daily production fluctuations and enabling off-grid or mobile deployment.

Typical practice in industrial settings is to size ammonia storage for 15 days of production to ensure buffer capacity between synthesis and demand cycles (IRENA & AEA, 2022). This principle is also relevant in small-scale contexts, especially where synthesis is subject to interruptions due to fluctuating renewable power availability.

Systems for intermittent or batchwise export (e.g., by truck or barge) may combine pressurised and semi-refrigerated storage to accommodate both local distribution and transport interface requirements (Humphreys, 2020).

5.3 Integration into plant design

Ammonia storage is not a stand-alone component but must be considered as an integral part of the overall plant design, especially in decentralised, small-scale systems where operational flexibility, intermittent renewable energy, and limited infrastructure strongly influence system layout.

A well-integrated storage solution allows for the decoupling of ammonia production from downstream consumption. This is particularly relevant for systems powered by fluctuating renewable energy sources such as photovoltaics or wind, where the ammonia synthesis unit may not operate continuously. Storage enables buffering between production peaks and demand cycles—whether for fertiliser application, electricity generation, or export.

From a design standpoint, the following factors are critical when integrating storage into a green ammonia plant:

- **Sizing:** Storage capacity should be dimensioned based on the variability of power supply and the consumption profile. For example, a system producing 5 t/day with irregular renewable input may require 10–15 days of buffer capacity (IRENA & AEA, 2022).
- **Thermodynamic integration:** In fully integrated systems, storage can be thermally linked with the ammonia synthesis unit—particularly relevant in cryogenic loops, where waste cooling can be reused or where the storage temperature facilitates downstream separation.
- **Startup/shutdown compatibility:** Ammonia synthesis units based on Haber-Bosch or alternative processes have ramp-up and cooldown times. Integrated storage allows smoother transitions and avoids the need for oversizing upstream components.
- **Distribution interfaces:** For mobile or decentralised use, ammonia may be transferred from local storage to smaller satellite tanks or mobile containers. The plant design must therefore consider filling systems, pressure staging, and loading procedures for safe and efficient handling.

Storage also defines key engineering interfaces: to synthesis, power management, and transport infrastructure. For instance, systems with solid-state ammonia production or alternative synthesis routes (e.g. electrochemical or plasma-based) may benefit from low-pressure storage integration or even direct product removal mechanisms to reduce system complexity and avoid energy losses in post-processing (Zhang et al., 2018; Rouwenhorst et al., 2019).

Moreover, as global green ammonia infrastructure expands, plant designs will increasingly need to adapt to local or regional logistics, whether for maritime export terminals, rail-based delivery points, or on-site consumption. This means that modular storage must be flexible in scale, compatible with future infrastructure upgrades, and safe across varying regulatory environments (Salmon, 2021; Verschuur, 2024).

Ultimately, a well-designed ammonia storage system enables not only operational autonomy, but also lowers risk, improves economic viability, and simplifies regulatory compliance, especially when tailored to the needs of decentralised, renewable-driven production systems.

6. Resource integration and co-benefits

Beyond producing green ammonia, decentralised and modular plants enable intelligent resource integration and local value creation. Unlike large centralised facilities, small-scale systems are often embedded in local environmental or agricultural contexts, where side streams such as oxygen, heat, and surplus electricity can be reused to enhance sustainability and efficiency.

One of the most valuable by-products of electrolysis is **oxygen**. For every kilogram of H_2 produced, approximately 8 kilograms of oxygen are released. In integrated systems, this oxygen can be reused in wastewater treatment and in aquaculture or greenhouse operations to boost biological activity.

Likewise, waste **heat from electrolysers** systems can be repurposed for space heating, process preheating, or even absorption cooling for farm buildings or cold storage facilities. Recent studies document effective heat recovery in systems combining H_2, heating and cooling to achieve significant efficiency gains (Khammal & Khouya, 2024).

Moreover, when **surplus electricity** from co-located PV or wind installations is not used for H_2 production, it can be temporarily fed into the public grid, stored in batteries, or redirected to other uses such as EV charging or heat pumps. This improves plant flexibility and supports grid services.

From a broader perspective, decentralised ammonia production strengthens local resilience by **reducing**

dependency on global supply chains, particularly in isolated regions or the Global South. Distributed green ammonia systems have the potential to bypass fossil-based fertiliser imports and support local energy autonomy and food security (Sheran Munasinghe & Krimer, 2024).

However, it is important to note that the integration of these additional use cases often entails further investments and complexity. Heat exchangers, oxygen purification systems, or grid interfaces can increase capital costs and require holistic planning. These co-benefits must therefore be considered as part of the overall system design, rather than as isolated add-ons.

Still, by viewing small-scale ammonia plants not only as production units but as local energy-resource hubs, new synergies can be unlocked, ecologically, economically, and socially. These ideas do not replace a solid process design, but they offer inspiration for future-oriented and resilient applications that go beyond conventional thinking.

7. Ammonia usage

Small-scale production of green ammonia not only decentralises its synthesis but also enables its use directly at or near the site of production. Unlike centralised plants that rely on national logistics chains for large-scale fertiliser or chemical distribution, decentralised units can serve a range of **local agricultural, industrial, or energy-related applications**.

7.1 Fertiliser production – on-site nitrate solution

One of the most direct and valuable applications is the production of liquid N_2 fertiliser. Ammonia (NH_3) can be converted on-site into ammonium nitrate solution by reaction with nitric acid (HNO_3), forming a concentrated fertiliser solution (NH_4NO_3) commonly used in precision agriculture. This liquid is then diluted to application concentrations (typically 20–32% N) and applied via drip or sprinkler irrigation systems. Compared to solid fertilisers, liquid forms allow for more efficient uptake, targeted dosing, and integration into fertigation systems.

A key advantage of local synthesis is the avoidance of long supply chains, reducing delays and fertiliser degradation during transport. This is especially important in regions where seasonal access, storage, or imports are challenging.

7.2 Energy carrier and transport

Green ammonia can also be used as an energy carrier. For transport, ammonia is typically stored and shipped in pressurised tanks (6–10 bar at ambient temperature) or refrigerated tanks (−33 °C at atmospheric pressure) Duijmet al., (2005), (Nayak-Luke et al., 2021). Small-scale plants may include buffer storage and loading stations for tank trucks, allowing supply to local farms, cooperatives, or industrial consumers.

While liquefied ammonia is classified as hazardous (UN No. 1005), its physical properties are well-known and manageable, and existing transport regulations for anhydrous ammonia apply. Transport distances are typically kept short (<100 km), especially in agricultural settings.

7.3 Industrial applications – micro users

Small industrial sites may also benefit from local ammonia supply. Potential applications include:

- NOx reduction in local incineration or biogas plants via Selective Catalytic Reduction (SCR) (Ştefan Cristian Galusnyak et al., 2023)
- Use in chemical processing (e.g. water treatment, pH adjustment),
- Operation of test systems, labs, or pilot-scale reactors in universities or R&D sites.

In such cases, ammonia can be delivered in pressurised cylinders or tanks, and usage volumes remain low, requiring only basic storage and safety infrastructure.

7.4 Explosives and nitrate compounds

Another, albeit more regulated application, is the production of ammonium nitrate for explosives, commonly used in mining and civil engineering (e.g. ANFO (Ammonium Nitrate Fuel Oil). While this is not the focus of most green ammonia projects, it is technically feasible at small scale and may be relevant in remote mining operations, where logistical independence is critical (Ştefan Cristian Galusnyak et al., 2023). However, such applications are strictly regulated and must comply with national safety, security, and export control regulations.

8. Summary and outlook

Decentralised, small-scale production of green ammonia is gaining increasing importance in the context of the global transition toward sustainable energy systems. In particular, the capacity range of 1 to 50 tonnes of NH_3 per day opens up new fields of application, from off-grid agricultural operations and island grids to industrial micro-sites. While large-scale plants continue to rely on the classical Haber-Bosch process in combination with centralised electricity and H_2 supply, modular-scale systems require a redesigned process configuration focused on decentralisation, flexibility, and integration with renewable energy sources.

Analysis of the process chain reveals that the key differences between large- and small-scale plants lie not only in scale, but especially in system integration, load management, and resource provision. Core components such as H_2 electrolysis, N_2 generation, water supply, and power buffering must be re-dimensioned, automated, and adapted for flexibility in small-scale systems.

At the heart of the technical challenge lies the selection of an appropriate ammonia synthesis process. Miniaturised Haber-Bosch reactors currently represent the only commercially mature technology for decentralised ammonia production and have proven to be a robust baseline solution. Their practical applicability under real-world conditions, such as fluctuating power supply and limited infrastructure, has been demonstrated by pilot plants like *TalusOne* in Kenya and modular systems developed by *Proton Ventures*. These examples show that off-grid, locally integrated NH_3 plants are already technically feasible.

Innovative approaches such as absorption-enhanced low-pressure synthesis, electrochemical processes, or non-thermal plasma technologies are still in the pilot or research stage but offer substantial potential for future deployment. Their strengths lie particularly in modularity, load flexibility, and strong compatibility with decentralised energy environments, making them promising candidates for emerging key technologies.

At the same time, these realised projects make clear that the successful implementation of small-scale ammonia systems requires an integrative interplay of renewable energy supply, storage, water treatment, and process control, and cannot be achieved through simple linear downscaling of conventional technologies.

A key development objective going forward must be to enhance the flexibility of ammonia synthesis processes so they can be operated economically under dynamic energy conditions. This includes adaptive control systems, intelligent storage buffers, and robust catalysts and separation units that can operate effectively at low temperatures and pressures. In parallel, regulatory incentives should be established to actively support small NH_3 systems as decentralised energy and fertiliser supply technologies, especially in regions with vulnerable infrastructure.

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