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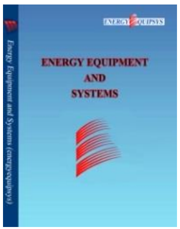

Techno-Economic analysis of centralized and decentralized ammonia cracking for clean hydrogen production

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ABSTRACT

Ammonia is increasingly recognized as a promising hydrogen carrier in the global shift toward low-carbon energy systems. Its high hydrogen content (17.6% by weight) established global infrastructure, and relatively simple storage and transport requirements make it an attractive alternative to direct hydrogen handling, which remains challenged by energy-intensive compression and liquefaction processes. This study presents a comprehensive techno-economic assessment of centralized and decentralized ammonia cracking systems. The lithium imide catalyst, evaluated in this study, achieves high ammonia conversion at lower operating temperatures compared to traditional ruthenium- and nickel-based catalysts, reducing energy demand and enhancing system compactness, making it particularly suitable for decentralized applications. These findings suggest that decentralized ammonia cracking, supported by next-generation catalysts like lithium imide, offers a more scalable and economically feasible approach for distributed hydrogen production. This research points to deploying distributed, point-of-use ammonia-to-hydrogen micro hubs at ports and industrial clusters as the most practical near-term pathway, leveraging existing ammonia logistics, and it underscores ammonia's role as the primary carrier for early markets.

Keywords: Hydrogen storage, Hydrogen Carrier, Ammonia cracking, Techno-Economic Analysis, Decentralized Hydrogen Production.

1. Introduction

The global push to reduce reliance on fossil fuels has created a growing demand for clean and flexible energy carriers [1],[2],[3],[4]. Several solutions have been suggested [5], [6], [7].

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Among them, Hydrogen is widely recognized as a key candidate in this transition, due to its potential to decarbonize sectors such as power generation, transportation, including aerospace and heavy industry where hydrogen is studied with CFD [8],[9], [10],[11]. When used, hydrogen produces no direct carbon emissions, making it an attractive option for sustainable energy systems, as several studies have confirmed [12],[13],[14],[15],[16],[17]. However, its widespread adoption faces significant challenges, particularly in terms of storage and transport[18], [19]. Hydrogen is a low-density gas that requires either high-pressure compression or cryogenic liquefaction, both of which involve high energy costs and complex infrastructure [20],[21].

Ammonia (NH_3) has emerged as a promising alternative to direct hydrogen handling. Containing 17.6% hydrogen by weight, ammonia offers a compact and energy-dense form of hydrogen storage. It remains a liquid under moderate pressures and temperatures, making it easier and more cost-effective to store and transport compared to molecular hydrogen. With a long-standing role in agriculture and chemical industries, ammonia already benefits from a global infrastructure network, including production facilities, storage systems, modeling [22], [23], [24] and transport logistics, that can be adapted for energy applications [25],[26], [27].

One of ammonia's most valuable features of ammonia is its ability to be synthesized using green hydrogen and atmospheric nitrogen. This makes it part of a potential low-carbon energy cycle. Once transported to a location where hydrogen is needed, ammonia can be thermochemically decomposed into hydrogen and nitrogen through a process known as ammonia cracking. This enables high-purity hydrogen to be produced on demand, close to the point of use, and supports a more flexible and distributed hydrogen supply chain[28],[29],[30],[31].

Ammonia cracking technologies are central to unlocking the full potential of ammonia as a hydrogen carrier. Two main approaches are currently under development: centralized and decentralized systems. Centralized cracking involves large-scale facilities that convert ammonia into hydrogen and distribute it through pipelines or via compression and delivery. While efficient at high volumes, this model incurs high capital and operational costs related to infrastructure and hydrogen transport. Decentralized systems, by contrast, bring ammonia directly to the point of use and generate hydrogen on-site. This approach reduces the need for hydrogen transport, minimizes compression requirements, and improves accessibility for end-use applications such as hydrogen refueling stations, distributed energy systems, and industrial sites[32],[33],[34],[35].

The effectiveness of ammonia cracking depends largely on catalyst performance. Traditional catalysts, such as those based on ruthenium and nickel, require high operational temperatures to achieve efficient decomposition. These conditions raise energy demand and limit the economic feasibility of large-scale deployment. Recent research has introduced new catalyst materials, such as lithium imide, that can operate at significantly lower temperatures. These advancements reduce both energy consumption and system costs while maintaining high conversion efficiency. Such improvements are particularly impactful for decentralized systems, where compact, low-energy reactors are required [36],[37],[38].

Progress in reactor design and thermal management has also contributed to improved system performance. Innovations in heat transfer, catalyst utilization, and modular reactor architecture have enabled more efficient ammonia conversion and better integration into a variety of energy systems[39],[40],[41].

Beyond national or regional applications, ammonia offers a solution for global renewable energy trade. Countries with abundant solar or wind resources can convert surplus electricity into hydrogen, synthesize ammonia, and export it to energy-demanding regions. Ammonia's stability and energy density make it suitable for long-distance shipping and cracking it back into hydrogen near the point of consumption enables clean energy to be shared internationally[42],[43],[44].

This paper explores the role of ammonia as a hydrogen carrier, with a particular focus on recent advancements in cracking technology, catalyst development, and system-level integration. It examines how centralized and decentralized ammonia decomposition systems can support hydrogen distribution and highlights the potential of ammonia to contribute to a scalable, global hydrogen economy.

2. Methodology

2.1. Benefits of Ammonia as a Hydrogen Carrier

Ammonia has emerged as a highly favorable vector for the large-scale storage and transportation of hydrogen, owing to a combination of advantageous thermophysical properties, infrastructure compatibility, and decarbonization potential. With a hydrogen content of approximately 18% by weight, ammonia serves as a high-capacity hydrogen carrier, outperforming alternatives such as liquid organic hydrogen carriers (LOHCs) and metal hydrides in terms of volumetric efficiency and ease of handling. Figure 1 demonstrates the projected transport volume of hydrogen and ammonia for energy purposes in 2050.

A key differentiator lies in ammonia's existing global production and distribution infrastructure, which is extensively utilized in the fertilizer industry. This widespread availability facilitates the integration of ammonia-based systems into emerging hydrogen supply chains with minimal logistical overhaul. Its phase stability under moderate conditions, liquefying at atmospheric pressure and –33°C, further enhances its suitability for storage and transport. This is in stark contrast to liquid hydrogen, which requires cryogenic conditions near –253°C, thereby incurring substantial energy and safety constraints.

A key parameter adding analytical complexity to the comparative assessment of hydrogen and ammonia as energy carriers is their respective energy degradation over time. Recent research highlights that hydrogen suffers energy losses due to compression, leakage, and material embrittlement, making it more suitable for short-duration storage where rapid response and high purity are essential. In contrast, ammonia is more stable over time and can be stored in liquid form or within metal salts with minimal degradation, making it advantageous for seasonal storage and global transport. Technological advancements are also improving ammonia's viability: electrolysis enhancements and low-pressure synthesis are projected to reduce energy input to approximately 7.9 MWh per ton of NH_3 by 2024, while innovations such as direct ammonia fuel cells and advanced cracking technologies could raise round-trip efficiency toward 50% in the coming decade.

Table 1 compares compressed hydrogen, liquid hydrogen, and ammonia (NH_3) as energy storage media based on energy input, energy stored, round-trip efficiency, and time suitability. Compressed hydrogen requires around 48 MWh per ton for electrolysis and stores approximately 33.6 MWh of energy, with a round-trip efficiency of about 42% when used in fuel cells and 17% in internal combustion engines, making it more suitable for short-term storage (hours to days). Liquid hydrogen stores a similar amount of energy (~33.6 MWh) but demands higher input energy due to the liquefaction process, yielding a round-trip efficiency between 30–40% and being more appropriate for medium-term storage.

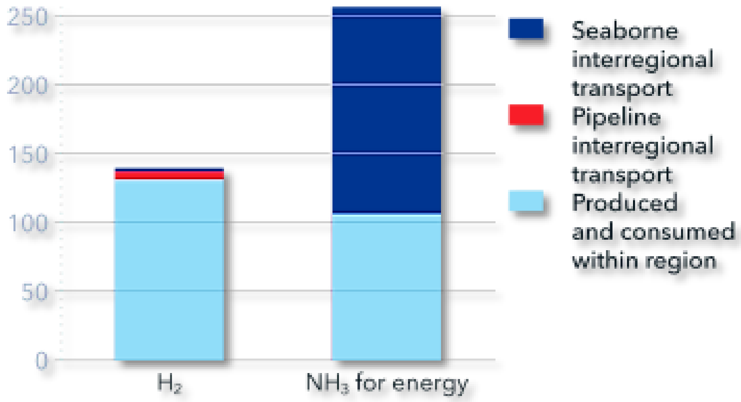

Fig. 1. Comparison of annual transport volumes for hydrogen (H_2) and ammonia (NH_3) by mode[45]

Table 1. Comparative characteristics of hydrogen and ammonia energy storage technologies.

Storage medium	Energy Input(per ton)	Energy Stored	Round-Trip Efficiency	Time Suitability
Compressed hydrogen	~48MWh(electrolysis)	~33.6MWh	~42%(fuel cell), ~17%(ICE)	Short-term (hours-days)
Liquid hydrogen	Higher due to liquefaction	~33.6MWh	~30-40%	Medium-term
Ammonia (NH_3)	~7.9-12MWh	~5.9MWh	~20-40% (depending on checking method)	Long-term (weeks-months)

Ammonia, on the other hand, offers a lower energy input range of about 7.9–12 MWh per ton and stores around 5.9 MWh of usable hydrogen energy, with a round-trip efficiency of 20–40% depending on the cracking method. Due to its chemical stability and minimal degradation, ammonia is particularly well-suited for long-term storage (weeks to months) and global transport, positioning it as a promising alternative for seasonal and distributed energy systems.

Figure 2 illustrates the net energy (in MWh) retained in 1 ton of hydrogen-equivalent (H_2-EQ) over a 360-day storage period across three scenarios. The blue line, representing liquefied hydrogen (H_2), begins at approximately 20 MWh and steadily declines into negative values, falling below –10 MWh by day 360, indicating substantial energy loss over time. The red line, corresponding to liquefied ammonia (NH_3) with cracking, starts just under 30 MWh, gradually decreases, and ends slightly above 20 MWh, reflecting a more moderate decline. In contrast, the dashed turquoise line, representing compressed hydrogen, remains constant at around 30 MWh throughout the period, suggesting an idealized scenario with no energy degradation. While compressed hydrogen appears to retain energy most effectively, its use is limited by storage challenges, safety risks, and operational complexity. As a result, ammonia is increasingly considered a more practical and reliable hydrogen carrier, offering better long-term storage performance than liquefied hydrogen.

From an environmental perspective, ammonia offers significant potential as a zero-carbon hydrogen carrier, particularly when synthesized via renewable pathways, such as water electrolysis powered by sustainable energy sources. In such cases, ammonia enables indirect hydrogen transport while maintaining the integrity of low-emission objectives.

Moreover, ammonia can be readily decomposed or "cracked" to release high-purity hydrogen, rendering it applicable across a diverse range of sectors, including fuel cell technologies, high-temperature industrial processes, and stationary power generation. The combination of high energy density, logistical feasibility, and alignment with green energy strategies positions ammonia as a pivotal enabler in the global transition toward a sustainable hydrogen economy.

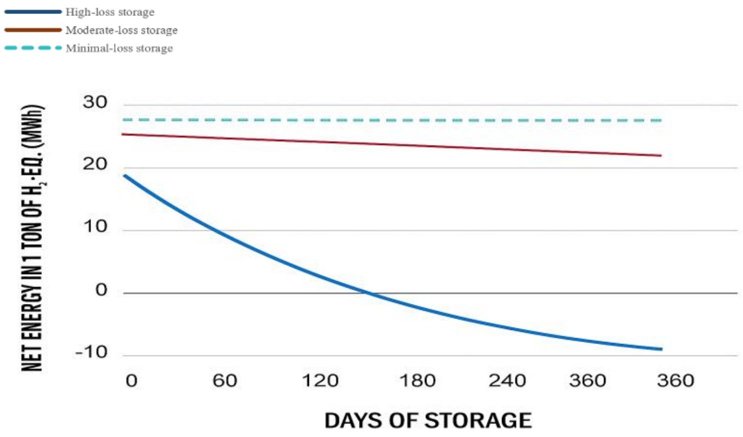

Fig. 2. Net energy retention over time for different hydrogen storage methods[45]

While centralized ammonia-to-hydrogen systems leverage economies of scale, their cost-effectiveness declines with increased hydrogen transport distance. In contrast, decentralized models can reduce delivered hydrogen costs by up to 30% within a 100 km radius by eliminating the need for extensive distribution infrastructure. Advances in cracking technologies, including membrane reactors and lithium imide catalysts, are enhancing the efficiency and scalability of both configurations.

The Hybrid Air-Volt Ammonia Cracker (HAVAC) is a groundbreaking innovation designed to enable centralized, carbon-free hydrogen production from ammonia. Developed through collaboration between Imperial College London and Saudi Aramco, HAVAC integrates renewable electricity and autothermal air-based operation to achieve exceptional performance. It boasts thermal efficiencies between 94% and 95%, ammonia conversion rates up to 99.4%, and hydrogen yields ranging from 84% to 99.5%, with purity levels reaching 99.99%fully compliant with ISO 14687:2019 standards for fuel cell applications. The system's core flexibility lies in its ability to operate in three distinct modes: fully electric, fully autothermal, or a hybrid of both, allowing it to adapt to varying energy sources and operational demands. A key component, the gas-heated cracker (GHC), utilizes waste heat to minimize energy consumption and enhance overall efficiency.

HAVAC was modeled using Aspen Plus simulation software and validated against experimental data, demonstrating not only technical feasibility but also economic viability. The levelized cost of hydrogen (LCOH) produced by HAVAC ranges between \$3.80 and \$6.00 per kilogram, making it competitive with other low-carbon hydrogen technologies. Its environmental advantages include reduced greenhouse gas emissions and effective NO_x management, positioning it as a promising solution for large-scale hydrogen deployment. Future research aims to further optimize catalyst performance, reduce ammonia feedstock costs, and scale up the technology for broader industrial use. HAVAC represents a major step forward in the pursuit of a sustainable hydrogen economy, offering a versatile and efficient pathway for clean energy production.

2.2. Ammonia Cracking Technologies

2.2.1. Centralized and Decentralized Models for Ammonia Cracking

A primary challenge in using ammonia as a hydrogen carrier lies in developing efficient and scalable ammonia cracking technologies. Ammonia cracking, the process of decomposing ammonia into hydrogen and nitrogen gases, requires high temperatures and is often hindered by kinetic barriers, making catalysts essential to improve reaction efficiency. The Ammonia to Green Hydrogen Project examines two primary models for ammonia cracking: the centralized and decentralized approaches. Together, these models address various logistical and economic considerations within the hydrogen supply chain, offering pathways to a more efficient hydrogen economy.

Centralized ammonia cracking suits large, steady hydrogen demand where efficiency and unit cost dominate. At industrial scale, plants can optimize heat integration, apply advanced emissions controls, and use high-performance catalysts, achieving strong thermal performance and economies of scale. Positioning facilities at ports or major hubs simplifies ammonia logistics and regulatory oversight while supporting thousands of tonnes per day for grids and heavy industry. The tradeoffs are substantial capital, complex permitting, long lead times, and vulnerability to supply-chain or demand swings; without low-carbon energy or capture, climate benefits can be diluted, and hub-and-spoke transport adds safety and distribution risks.

Decentralized ammonia cracking places modular units near the point of use, such as fueling stations, microgrids, or industrial sites. This avoids hydrogen transport, leverages ammonia's easy storage, enables incremental deployment, and pairs well with local renewables in urban, remote, or underserved areas. Constraints include weaker heat-recovery efficiency at small scale, higher sensitivity to impurities, costlier catalysts, limited load-following in many designs, and higher site-specific costs for ammonia delivery and safety systems.

In practice, centralized plants deliver the lowest cost for bulk, continuous demand, while decentralized units excel where flexibility, speed, and proximity matter. A phased regional strategy can combine import or production hubs for industry with distributed micro hubs for mobility and remote loads, balancing efficiency with access and resilience.

Beyond technical and economic hurdles, safety, logistics, and environmental concerns also pose significant barriers. The widespread handling of ammonia increases risks of toxicity and leakage, necessitating strict safety protocols and trained personnel. Regulatory challenges include the lack of standardized codes for small-scale systems, complicating permitting and public acceptance, especially in residential areas. Logistically, distributing ammonia to numerous sites is complex and demands expanded infrastructure for transport and storage. Maintenance across dispersed units requires remote monitoring and predictive diagnostics to ensure reliability. Environmentally, small units may lack adequate emission control technologies, raising concerns about NO_x and ammonia slip. Moreover, if fossil fuels are used for heat input, the carbon footprint of decentralized cracking could offset the environmental benefits of hydrogen production.

2.2.2. Methods of Ammonia Cracking

Ammonia cracking, the decomposition of ammonia (NH_3) into hydrogen (H_2) and nitrogen (N_2), is gaining traction as a clean method for producing hydrogen for applications such as fuel cells, industrial processes, and energy import hubs. Several techniques are employed for this process, with thermo-catalytic cracking being the most established. It operates at temperatures ranging from 500 to 900°C, utilizing catalysts such as nickel, ruthenium, or perovskites in tubular or adiabatic reactors. Electrochemical cracking uses electricity at lower temperatures, offering potential for decentralized hydrogen generation, but faces efficiency and scalability challenges. Photocatalytic cracking, which employs light and semiconductors or plasmonic photocatalysts, is eco-friendly but remains experimental due to low conversion rates. Plasma-assisted cracking utilizes plasma to break molecular bonds, suitable for niche applications requiring high-purity hydrogen. Membrane reactor systems, incorporating palladium-based membranes, allow simultaneous cracking and hydrogen separation, producing fuel-cell-grade hydrogen and are used by companies like H2SITE and Siemens[46].

The effectiveness of ammonia decomposition hinges largely on the catalysts used. Noble metal catalysts, especially ruthenium, are highly active at lower temperatures (~400°C) but expensive; platinum, palladium, and iridium are also employed with varying efficiency. Non-noble metal catalysts such as nickel, iron, and cobalt offer cost benefits but often require higher operating temperatures. Bimetallic and alloy catalysts (e.g., Ni–Fe, Ru–Pt) enhance performance by optimizing surface and electronic properties. Supported catalysts use materials like alumina, silica, and carbon nanotubes to improve dispersion and thermal stability. Emerging materials, including perovskites, metal nitrides like Co_3Mo_3N, and alkali metal amides, are under exploration for their promising catalytic behavior and novel reaction pathways.

2.2.3. Development of the Lithium Imide Catalyst

A significant advancement in ammonia cracking technology is the development of a lithium imide catalyst. Traditional catalysts, such as ruthenium- and nickel-based systems, necessitate high temperatures (exceeding 450°C) to achieve substantial conversion rates, rendering them both costly and energy-intensive, which restricts their scalability. The lithium imide catalyst, however, presents several notable advantages[47],[48],[49].

First, it enables high conversion rates at lower temperatures, significantly reducing the energy input required for ammonia decomposition and thereby enhancing overall process efficiency. Second, the lithium imide system demonstrates superior catalytic activity relative to conventional catalysts, lowering the temperature needed for 90% ammonia conversion by approximately 50°C, which improves both the economic feasibility and performance of the process. Lastly, lithium is more abundant and cost-effective than ruthenium, making the lithium imide catalyst more suitable for large-scale applications and effectively reducing the overall cost associated with ammonia cracking systems. These characteristics position the lithium imide catalyst as a promising solution for advancing scalable, efficient ammonia cracking technology[50],[51],[52].

Table 2 presents a comparative overview of three key catalyst types used in ammonia decomposition: lithium amide ($LiNH_2$), ruthenium-based (Ru), and nickel-based (Ni) catalysts. Lithium amide, an alkali metal amide, forms lithium imide (Li_2NH) under heat and is considered an emerging material for ammonia decomposition due to its unique reactivity. Ruthenium-based catalysts, composed of noble metals typically supported on Al_2O_3 or carbon, are known for their high performance and are widely regarded as benchmark catalysts for ammonia cracking. Nickel-based catalysts, being transition metals usually supported on Al_2O_3 or $MgAl_2O_4$, serve as the industrial standard owing to their cost-effectiveness and robust performance in both reforming and cracking applications. This comparison highlights the trade-offs between performance, cost, and technological maturity among catalyst options.

Table 3 compares the performance characteristics of lithium amide, ruthenium-based, and nickel-based catalysts for ammonia decomposition. Lithium amide exhibits high activity at moderate temperatures (300–540°C), especially when promoted with transition metals like Mn or Cr and operates through the formation of Li_2NH and Li_4NH intermediates. It delivers high hydrogen purity suitable for PEM fuel cells and shows good durability when composited with transition metals. Ruthenium-based catalysts stand out with very high activity even at lower temperatures (~400°C), utilizing a highly efficient surface-mediated mechanism. They produce very pure hydrogen, ideal for fuel cell applications, and offer excellent long-term durability. In contrast, nickel-based catalysts show only moderate activity, requiring higher temperatures (>600°C), and their surface-mediated mechanism is less efficient than ruthenium. While more affordable, they yield lower hydrogen purity often necessitating further purification, and suffer from issues like sintering and carbon deposition, affecting long-term durability.

Table 2. Comparative characteristics of lithium amide, ruthenium-based, and nickel-based catalysts

Catalyst Type	Composition & Structure	Typical Use Case
Lithium Amide ($LiNH_2$)	Alkali metal amide; forms lithium imide (Li_2NH) under heat	Emerging catalyst for ammonia decomposition
Ruthenium-Based (Ru)	Noble metal is often supported on Al_2O_3 or carbon	High-performance catalyst for ammonia cracking
Nickel-Based (Ni)	Transition metal, often supported on Al_2O_3 or $MgAl_2O_4$	Industrial standard for reforming and cracking

Table 3. Comparative Performance of lithium amid, ruthenium-based, and nickel-based catalysts

Property	Lithium Amide	Ruthenium-Based	Nickel-Based
Activity	High at moderate temperatures (300–540°C) when promoted with transition metals like Mn or Cr	Very high, even at lower temperatures (~400°C)	Moderate; requires higher temperatures (>600°C)
Mechanism	Involves the formation of Li_2NH and Li_4NH intermediates	Surface-mediated decomposition; highly efficient	Surface-mediated; less efficient than Ru
Hydrogen Purity	High; suitable for PEM fuel cells	Very high; ideal for fuel cells	Lower; may require purification
Durability	Good when composited with transition metals	Excellent; stable over long durations	Prone to sintering and carbon deposition

3. Results and Discussion

3.1. Large-Scale Ammonia Cracking Models

The study examines the design and feasibility of a large-scale ammonia cracking plant capable of producing 200 tonnes of hydrogen daily, based on a fired reformer configuration with integrated heat recovery systems to maximize energy efficiency. This system generates a forming gas mixture of hydrogen, nitrogen, and uncracked ammonia, with the latter recycled through an ammonia recovery unit to enhance efficiency. Key features of the plant include its high thermal efficiency of 93.1%, achieved by capturing waste heat from the flue gas to preheat feedstock and generate steam; an ammonia recovery process using water absorption to minimize ammonia loss; and cryogenic purification to reach a hydrogen purity of 99.97% by removing nitrogen and residual ammonia. Designed to deliver high-purity hydrogen at 250 bars, this plant model is well-suited for diverse applications, including fuel cell vehicles and industrial processes. As illustrated in Fig.3, the system's main components include the fired reformer, heat recovery unit, ammonia recovery unit, and cryogenic purification section. These units operate together as an integrated process that supports a continuous and efficient hydrogen-production cycle from the ammonia feedstock.

Currently, there are no known technologies capable of decomposing ammonia at large industrial scales, with most available systems relying on electric furnaces that produce only 1 to 2 tonnes per day. These units typically generate a forming gas composed of hydrogen and nitrogen for general industrial use but seldom achieve high-purity hydrogen output. In contrast, this study presents the design and evaluation of a large-scale ammonia plant engineered to produce hydrogen suitable for fuel cells. Using Aspen Suite simulation software and a two-step iterative modeling approach, the ammonia reformer was developed with attention to the trade-off between conversion efficiency and thermal performance.

We compute thermal efficiency as

$$\eta_{th} = \frac{Q_{H2}}{Q_{in}} \qquad (1)$$

$$Q_{H2} = m_{H2} * LHV_{H2} \qquad (2)$$

Table 4 benchmarks thermal/process efficiency for ammonia cracking across three designs. Conventional routes without advanced heat integration reach roughly 74–83% efficiency; the current industrial baseline is ~80%. In contrast, large, well-integrated plants, with effective heat recovery and modern catalysts can achieve up to ~96%. The spread shows how heat integration and catalyst performance drive higher efficiency, while less-integrated setups are limited by heat-transfer losses.

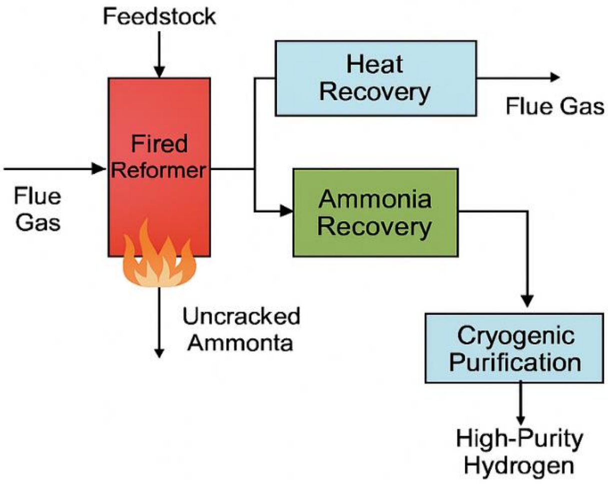

Fig. 3. Conceptual image showing the key elements of the ammonia cracking system for hydrogen production[53],[54]

Table 4. Thermal efficiencies of ammonia cracking technologies.

Situation / Example	Thermal / Process Efficiency
Conventional ammonia cracking routes (no advanced heat integration)	~74 % to ~83 %.
Large-scale, well-integrated plants using good heat recovery & catalysts	Up to ~96 %.
Current industrial "baseline" for many ammonia crackers	Around 80 %.

To enhance the overall thermal efficiency of the fired reformer design, a series of convection banks were implemented to recover heat from the flue gas. The table below presents the composition and operating conditions of each stream. The convection section is divided into four banks, each serving a specific role: the first functions as a feedwater evaporator, the second as an ammonia process evaporator, the third as a high-pressure steam superheater, and the fourth as a combustion air preheater. This arrangement enables the recovery of nearly all the available heat from the flue gas exiting the firebox. As a result, the overall thermal efficiency of the system reaches 93.1%, with an ammonia conversion rate of 84.6%.

3.2. Economic assessment of Ammonia cracking

An economic analysis of the centralized and decentralized cracking models considers various factors, including capital investment, operational expenses, and the overall cost of hydrogen production.
Figure 4 illustrates the purchased equipment cost distribution for centralized and decentralized ammonia cracking units, highlighting the differences in cost allocation between the two configurations. In centralized crackers, the major cost components are reforming (31%), purification (28%), and compression (25%), followed by smaller contributions from cogeneration (8%), cooling utilities (5%), and ammonia recovery (3%). This breakdown reflects the complexity and scale of centralized systems, which require extensive purification and compression infrastructure to deliver high-purity hydrogen at large volumes. In contrast, decentralized crackers allocate a dominant 70% of costs to reforming, with much smaller shares for instrumentation (14%), compression (9%), and skid and insulation (7%). The simpler cost structure of decentralized systems emphasizes their streamlined design, making them suitable for small-scale, localized hydrogen generation with lower equipment complexity compared to centralized plants.

3.3. Centralized model

The capital investment for a centralized ammonia cracking facility with a production capacity of 200 tons of hydrogen per day is estimated at £368 million. The overall hydrogen production cost is projected to range from £4.79 to £5.19 per kilogram, contingent on operational variables such as electricity prices and ammonia feedstock costs. Although the centralized model benefits from economies of scale, it incurs substantial expenses associated with hydrogen transportation and compression.

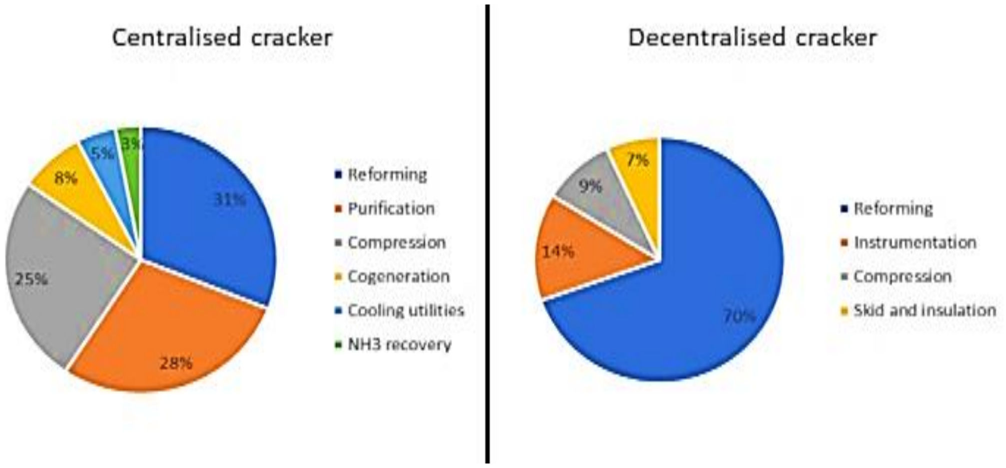

Fig. 4. Purchased equipment breakdown for centralized and decentralized ammonia cracking units[45]

The cost of delivering hydrogen from the centralized facility to end-users within a 100-kilometer radius is estimated at £49.44 per MWh, primarily due to the need for high-pressure hydrogen compression and storage. As shown in Table 5, these economic components, capital expenditure, production cost, and delivery cost, collectively define the financial feasibility of centralized hydrogen production, underscoring the importance of optimizing both plant efficiency and logistics infrastructure to ensure competitive pricing.

3.4. Decentralized model

The decentralized cracking model provides a more cost-effective solution for hydrogen production when ammonia transportation over long distances is required. The capital investment for a decentralized cracker with a capacity of 200 kg per day is estimated at £482,000 (equivalent to £482 million per 200 tons), yielding an overall hydrogen production cost of £4.65 per kilogram, with potential reductions to £4.09 per kilogram achievable through technological advancements. By enabling ammonia cracking directly at the site of use, the decentralized model circumvents the high costs associated with hydrogen transportation. This approach is especially beneficial for distributed energy systems and applications where hydrogen is needed at the point of consumption. As illustrated in Table 6, the economic profile of the decentralized system reflects its affordability in both capital and operational terms, while maintaining delivery costs comparable to centralized models, making it a practical option for localized, off-grid, or remote hydrogen supply scenarios.

Figure 5 presents a detailed cost breakdown for centralized and decentralized ammonia decomposition strategies, expressed in £/MWh of hydrogen. In the centralized model, the dominant cost component is hydrogen reforming at 250 bar, amounting to £141.43/MWh, followed by hydrogen transport (£21.61/MWh) and storage (£27.83/MWh), with additional costs for ammonia import and storage (£7.86/MWh). This results in a relatively high overall hydrogen cost due to the need for transporting and storing pressurized hydrogen. In contrast, the decentralized model significantly reduces transport and storage expenses by cracking ammonia closer to the point of use. Reforming costs are lower at £122.86/MWh, while hydrogen transport drops to zero, and storage costs fall to £6.13/MWh. Ammonia transport (£4.72/MWh) and import/storage (£7.86/MWh) remain, but the total cost is substantially reduced. This comparison highlights the economic advantage of decentralized systems in minimizing distribution-related expenses while maintaining competitive reforming costs.

Table 5. Economic analysis for capital investment per 200-kg hydrogen, per 1 kg hydrogen, and Delivery cost for 100 km [53],[54]

Cost Categories	Cost Value
Capital Investment	368 000 000(£)
Hydrogen production cost(Min)	4.79(£/kg)
Hydrogen production cost(Max)	5.19(£/kg)
Delivery cost	49.44(£/MWh)

Table 6. Economic analysis for capital investment per 200 kg hydrogen, per 1 kg hydrogen, and Delivery cost for 100 km [53], [54]

Cost Categories	Cost Value
Capital Investment	482 000 000(£)
Hydrogen production cost(Min)	4.09(£/kg)
Hydrogen production cost(Max)	4.65(£/kg)
Delivery cost	49.44(£/MWh)

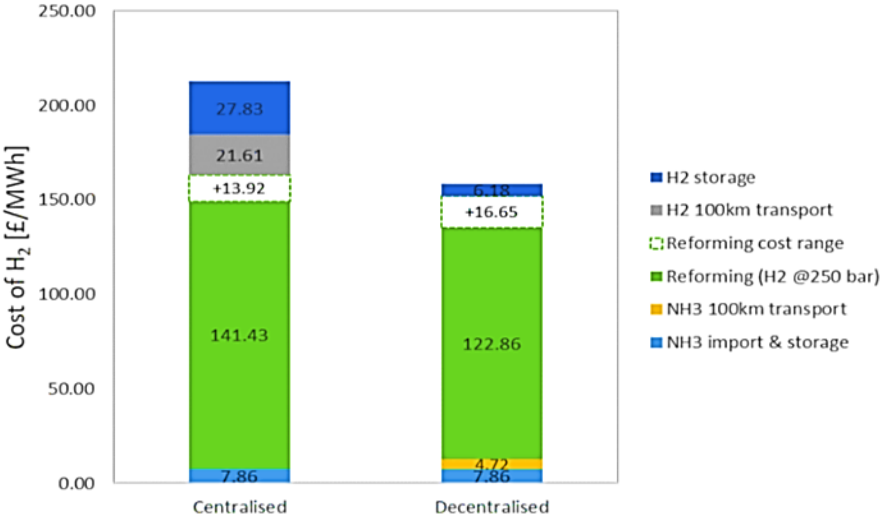

Fig.5. Cost breakdown for both ammonia decomposition strategies [45]

3.5. Cost Comparison of Catalysts in Ammonia Decomposition

Ruthenium-Based Catalysts offer outstanding efficiency at low temperatures and high hydrogen yield, but they are expensive due to ruthenium's status as a platinum-group metal. Operational savings and recyclability help offset the cost, making them effective for high-performance applications. Nickel-based catalysts are affordable and widely available, making them practical for industrial use. While they require higher temperatures and energy input, they strike a good balance between cost and catalytic performance. Lithium Amide Catalysts are low-cost and composed of earth-abundant materials. Their efficiency can match or exceed alternatives when enhanced with transition metals. However, they demand specialized equipment and handling, adding complexity. They're promising for decentralized hydrogen production where cost and flexibility matter. As shown in Figure 6, ruthenium-based catalysts also benefit from the lowest activation energy (~25 kJ/mol), enabling superior reactivity at lower temperatures, while lithium amide exhibits the highest activation energy (~88 kJ/mol), explaining its need for thermal promotion. Nickel-based catalysts fall in between, with moderate activation energy (~50 kJ/mol), consistent with their performance profile.

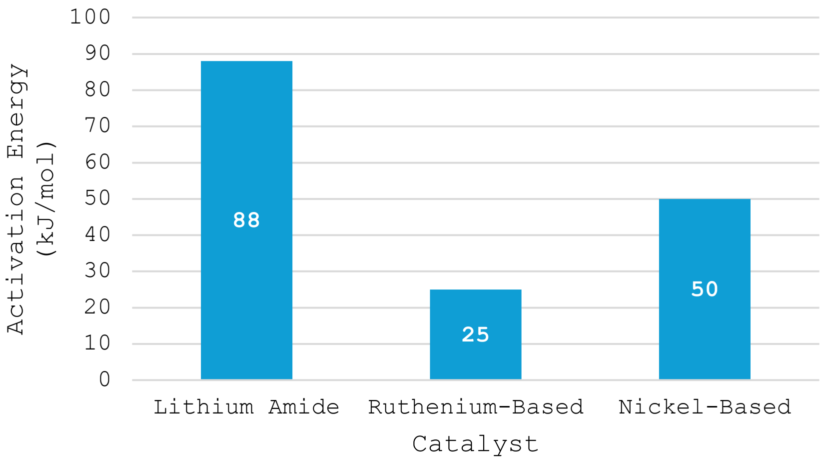

Fig.6. Energy activation of catalysts for ammonia decomposition [53],[54]

Table 7 provides a comparative assessment of the cost and availability of lithium amid, ruthenium-based, and nickel-based catalysts, focusing on three key factors: material cost, scalability, and environmental impact. Lithium amide stands out for its low to moderate cost and use of earth-abundant elements, resulting in a low environmental footprint. However, its scalability remains limited as the technology is still under development. Ruthenium-based catalysts, while offering excellent performance, are hindered by high material costs due to their reliance on precious metals. Their scalability is restricted by both cost and limited resource availability, and their environmental impact is significant due to the intensive mining and refining required. In contrast, nickel-based catalysts strike a balance between affordability and scalability; they are low-cost, widely used, and relatively easy to scale. Their environmental impact is moderate, making them a practical and accessible option for large-scale hydrogen production, particularly where cost and maturity are key considerations.

Figure 7 illustrates the catalytic ammonia decomposition performance of various catalysts, including lithium amide, sodium amide, ruthenium on alumina, and nickel on silica-alumina, compared to a blank reactor. The plot shows ammonia conversion (%) as a function of temperature (°C), highlighting the temperature-dependent activity of each catalyst. Lithium amide exhibits the highest conversion rate, achieving nearly complete decomposition (~100%) at around 475°C, outperforming all other catalysts tested. Sodium amide and ruthenium on alumina also demonstrate high activity, reaching over 90% conversion at similar temperatures, with ruthenium being slightly more efficient at lower temperatures (~400°C). Nickel on silica-alumina shows moderate performance, with conversion increasing steadily with temperature but not reaching full decomposition within the tested range. The blank reactor exhibits minimal conversion, confirming that catalytic enhancement is essential. Overall, the results underscore the effectiveness of lithium and sodium amides as promising non-precious catalysts for ammonia decomposition, especially in thermally optimized systems

Table 7. Comparative Cost and Availability of lithium amide, ruthenium-based, and nickel-based catalysts

Factor	Lithium Amide	Ruthenium-Based	Nickel-Based
Material Cost	Low to moderate	High (precious metal)	Low
Scalability	Promising but still under development	Limited by cost and availability	Widely used and scalable
Environmental Impact	Low; earth-abundant elements	High; mining and refining are intensive	Moderate

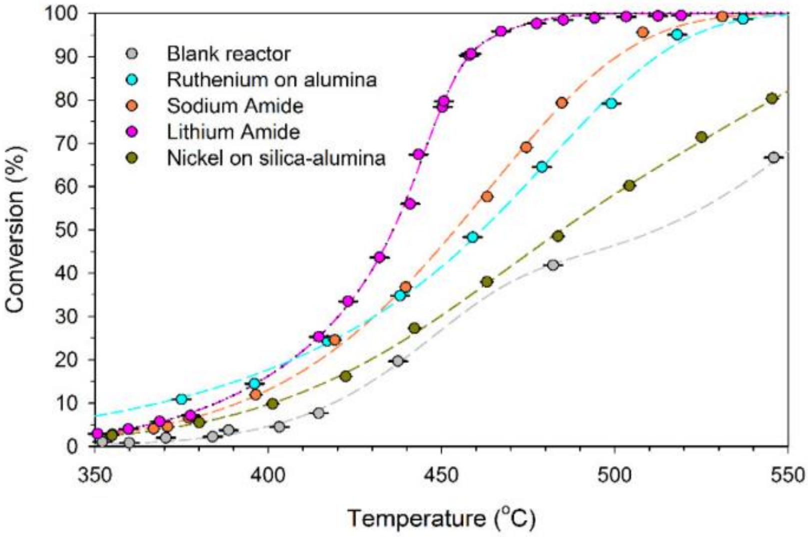

Fig. 7. Catalytic ammonia decomposition performance of lithium and sodium amide compared with supported nickel and ruthenium catalyst[45]

4. Conclusion

This study confirms ammonia's viability as a hydrogen carrier, enabled by catalytic innovations in cracking. Centralized systems offer high-volume efficiency but face limitations from compression and transport requirements. Economic evaluations further reinforce that decentralized models can substantially lower hydrogen delivery costs, particularly where infrastructure is limited. As countries invest in renewable energy exports and hydrogen hubs, ammonia stands out as a scalable, stable, and globally tradeable medium. Its integration into hydrogen supply chains will be essential to achieving carbon-neutral energy systems.

From a broader perspective, the economic success of ammonia-based hydrogen systems depends heavily on smart technology choices and system design. Decentralized approaches stand out for their lower startup and operating costs, and as these technologies continue to improve, they're likely to become even more cost-effective. In the long run, expanding the use of these systems could reduce the overall price of clean hydrogen, support job growth in new energy sectors, and make sustainable energy more accessible in under-served areas. Overall, our results position ammonia cracking as a practical, scalable option for near-term deployment, solidifying ammonia as the backbone carrier for early hydrogen markets. By leveraging existing ammonia storage, shipping, and safety protocols, projectors can reach bankability faster and de-risk early volumes without waiting for new hydrogen pipelines.

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