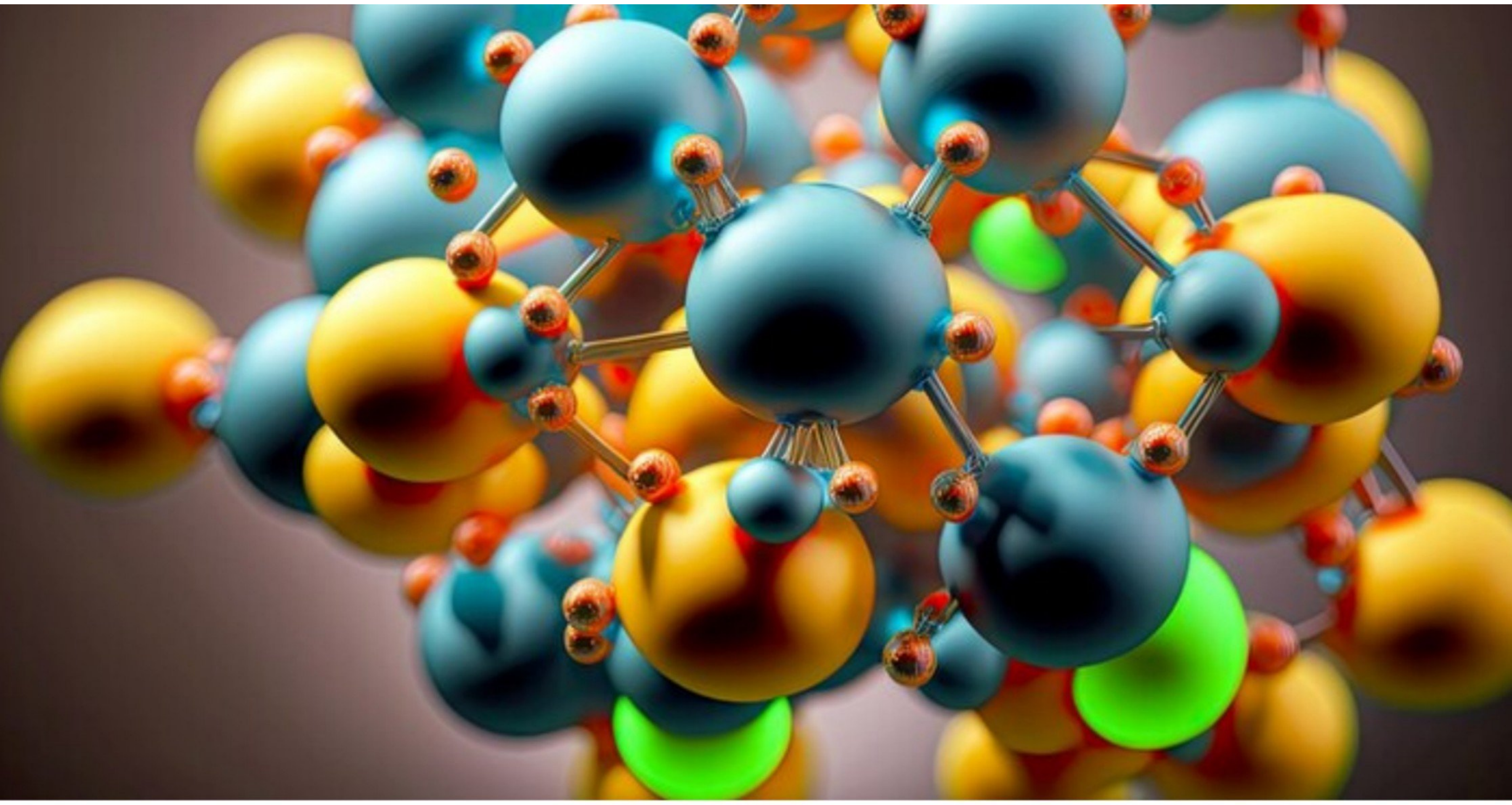
H2LENS

AMMONIA'S ROLE IN THE ENERGY TRANSITION:

A PATH TO DECARBONISATION AND GREEN ENERGY SOLUTIONS

AUTHORS

•Ayodeji Stephen
Lead Researcher, Hydrogen Lens
•Aisha Suleiman
Associate Researcher, Hydrogen Lens
•Joy Mampak
Associate Researcher, Hydrogen Lens
•Steve Agai
Associate Researcher, Hydrogen Lens



EXECUTIVE SUMMARY

Ammonia is emerging as a key player in the transition to sustainable energy systems, offering significant potential for reducing CO2 emissions and facilitating the adoption of renewable energy sources. Its unique composition of nitrogen and hydrogen makes it an attractive option for dense energy storage, ease of processing, and environmental safety, particularly as a hydrogen transporter. Ammonia's versatility extends to various industries, including power generation and transportation, where it can be used as a fuel in direct ammonia fuel cells and as a substitute for conventional fuels.

Research and development efforts are focusing on addressing persistent challenges such as energy efficiency and safety concerns to unlock the full potential of ammonia as a sustainable energy solution. The PtA process, which converts surplus electricity from sporadic renewable sources into ammonia, further enhances its appeal as a versatile energy source that can be generated and stored.

Ammonia's adaptability is further underscored by the existing agricultural infrastructure, which facilitates distribution and transportation. The anticipated growth of the green ammonia market globally highlights the industry's dynamism and decarbonisation potential. Global initiatives and legislative backing are driving technological progress and adoption, as outlined in the IEA's roadmap.

As nations strive to achieve their sustainability targets, collaboration among industry stakeholders is essential to overcome challenges and accelerate the deployment of green ammonia technologies. Adequate funding for legislative frameworks, infrastructure development, and research is crucial to fully harnessing ammonia's potential as a sustainable energy source.
By working together, industry stakeholders can leverage ammonia's capabilities to create a greener, cleaner future for generations to come.

INTRODUCTION

Industrial activities in different parts of the world harm the environment because they lead to the emission of carbon dioxide (CO_2), a natural greenhouse gas that helps to keep the globe warm. Its concentration has increased, thereby causing the climate crisis. This anthropogenic emission endangers human health, agriculture, natural ecosystems, and atmospheric stability. As reported in the Intergovernmental Panel on Climate Change (IPCC) Climate Change Mitigation Report (2014), CO_2 is the main contributor to GHG Emissions.

Global energy sources are being transformed from hydrocarbon-based energy sources to renewable and carbon-free energy sources such as wind, solar, and hydrogen.
The complexity of hydrogen as a renewable energy carrier is the storage and delivery system's biggest challenge. Therefore, other media, such as Ammonia for indirect storage, are now being considered.
Research has shown that Ammonia is easily contained as a liquid at reasonable pressures. In this form, energy density is approximately half that of gasoline and ten times more than batteries.

Ammonia can provide effective storage of renewable energy through its existing storage and distribution network.
This white paper focuses on Ammonia as a sustainable energy carrier.
Ammonia is now strongly regarded as fuel in the transport, industrial and power sectors and is relatively more versatile in reducing CO_2 emissions.
Therefore, the utilisation of Ammonia as a renewable energy carrier plays a significant role in reducing GHG emissions. Also, the simplicity of Ammonia processing, transport, and use makes it an appealing choice as a sustainable energy carrier.

Introduction Cont'd

A sustainable energy carrier is any material that can store, transport, and deliver energy in a way that reduces environmental impact and promotes sustainability. Sustainable energy carriers are crucial in the transition from fossil fuels to clean energy. Below are some of the importance of sustainable energy carriers;

Sustainable energy carriers contribute to lowering CO2 and other greenhouse gas emissions, helping combat climate change because traditional energy sources, like coal and oil, contribute significantly to global warming.

The use of a variety of sustainable energy carriers reduces dependence on a single energy source, thereby enhancing energy security, especially for countries that heavily rely on imported fossil fuels.

Sustainable energy carriers can store and transport energy generated from renewable sources like wind and solar, which are often plagued with intermittency.

The production, research, and deployment of sustainable energy carriers can create new job opportunities.

Ammonia can be a hydrogen carrier since it contains three hydrogen atoms per molecule, making it a dense hydrogen storage medium.

Ammonia: A Sustainable Energy Carrier

Ammonia is an inorganic chemical compound made up of nitrogen and hydrogen. Ammonia, the most basic pnictogen hydride and a stable binary hydride, is a colourless gas with a strong odour. It is a frequent nitrogenous waste from a biological perspective, and because it acts as a precursor to fertilisers, it greatly meets the nutritional needs of terrestrial species. The majority of Ammonia produced industrially—roughly 70%—is used in fertilisers. Even though Ammonia is widely used and found in nature, especially on Earth and in the outer planets of the Solar System, concentrated forms of it can be dangerous and corrosive. Facilities that produce, store, or utilise it in large quantities are subject to stringent reporting requirements as it is categorised as a very dangerous material in many nations.

AMMONIA; A SUSTAINABLE ENERGY CARRIER CONT'D

Energy is one of the most significant subjects in human life, and most of the energy produced overall throughout human history has come from the combustion of traditional fuels like coal. Due to the large global population and associated industrial activities, there is a growing need for energy, which raises carbon and greenhouse gas (GHG) emissions. These emissions come from a variety of combustion activities that produce energy for transportation, industry, and the production of electricity. These processes also have a significant negative impact on the ecosystem, which is a contemporary concern. Carbon dioxide (CO_2) is the most dangerous greenhouse gas (GHG) that raises atmospheric temperature; on its own, CO_2 accounts for around 30% of the global warming effect. Since combustion is a major source of greenhouse gas emissions, it is anticipated that using biofuels and renewable energy sources in place of conventional fossil fuels will lower carbon emissions. However, the intermittent nature of the majority of renewable energy sources, such as solar, wind, and tidal power, brings up the question of energy storage, specifically its expense and inefficiency. Moreover, it is challenging to replace traditional industrial burners everywhere. As a result, it is crucial to find a substitute fuel for traditional fossil fuels.

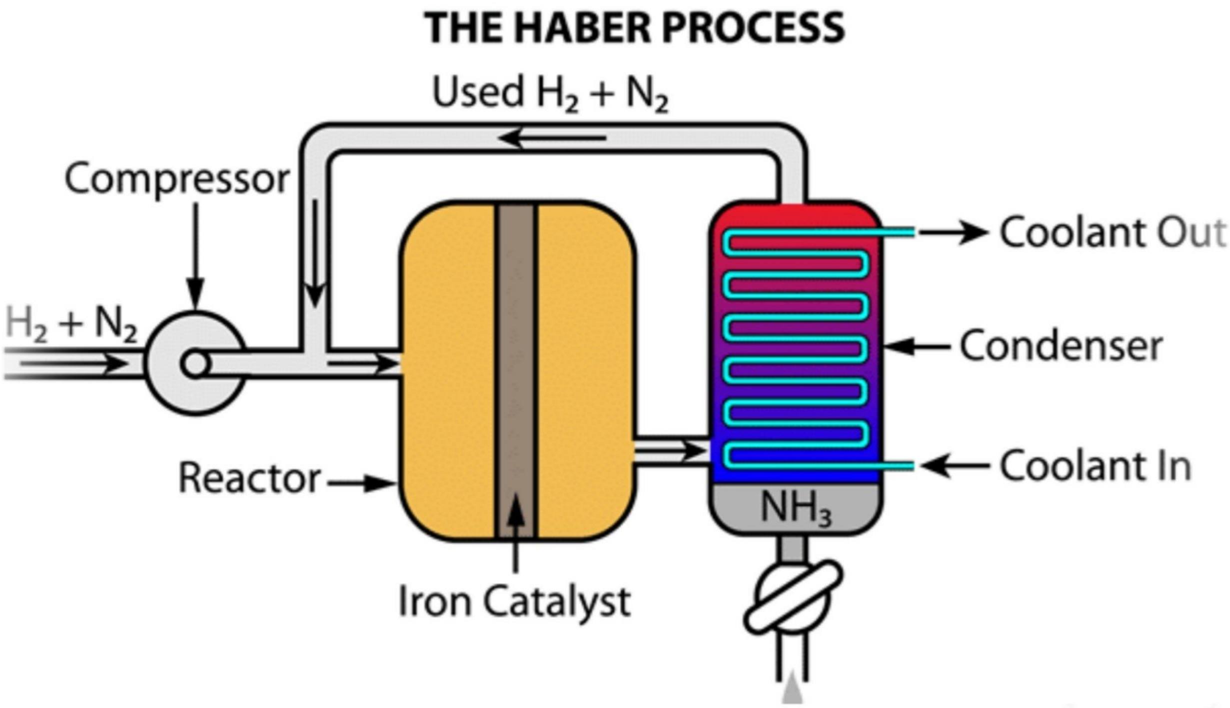
Ammonia is a viable substitute for hydrogen since it is an effective hydrogen carrier. It is a more practical option since it can obtain more hydrogen than liquid hydrogen because it typically delivers a higher hydrogen density per unit volume. Furthermore, large-scale Ammonia production is highly steady now due to the need for commercialisation, dating back more than a century.

However, the ease with which Ammonia may be liquefied compared to pure hydrogen and its high degree of similarity in storage requirements with another fuel utilised in commerce, propane, greatly lower the costs involved with development and transportation.

Numerous attempts have been made recently to employ Ammonia in gas turbines and internal combustion engines. For example, in the context of microgrid proceedings, the California Public Utilities Commission met with industry stakeholders to discuss alternatives to diesel generators.

Ammonia has many significant benefits as a possible fuel, some of which are as follows:

- It is safe for the environment and produces no carbon.
- It possesses three hydrogen atoms and could be employed as a hydrogen transporter.
- Compared to many other fuels, producing, storing, transporting, and distributing Ammonia is far simpler and easier.
- For applications, it is both inexpensive and practical.
- It can be thought of as a possible substitute for kerosene, diesel, and gasoline.
- It is applicable to all combustion systems, including gas turbines and engines.
- In isolated locations, it might provide a fuel option for the production of clean electricity.



CHEMICAL PROPERTIES OF AMMONIA

Ammonia burns slowly but produces water and nitrogen gas as byproducts.

$4NH_3 + 3O_2 + heat \rightarrow 2N_2 + 6H_2O$

However, Ammonia and oxygen combine to form nitric oxide (NO), which is then oxidised to nitrogen dioxide (NO_2) and employed in the industrial manufacture of nitric acid when a catalyst is applied and the temperature is just right.
When heat is released, Ammonia dissolves easily in water.

$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$

One common nonaqueous solvent is liquid Ammonia. Blue solutions are produced when the alkali metals, heavier alkaline-earth metals, and even certain inner transition metals dissolve in liquid Ammonia. Physical investigations, such as studies of electrical conductivity, show that the solvated electron is responsible for the blue colour and electrical current.

$Metal\ (dispersed) \rightleftharpoons metal(NH_3)_x \rightleftharpoons M^+(NH_3)_x + e^-(NH_3)_y$

CONVENTIONAL AMMONIA PRODUCTION

The currently adopted Ammonia production process basically employs the system invented by Fritz Haber and Carl Bosch about 100 years ago. Therefore, this system is well known as the Haber–Bosch process. About 85% of the total production of Ammonia worldwide is produced by this process.
The Ammonia synthesis occurs according to the reaction:

$3 H_2 + N_2 \leftrightharpoons 2 NH_3 \quad \Delta H^\circ 27\ ^\circ C = -46.35$ kJ/mol

ELECTROCHEMICAL PROCESSING

Although electrochemical processing is significantly under-developed compared to the Haber–Bosch process, it is expected to realise higher energy performance. The energy consumed by this process is about 20% lower than the Haber–Bosch process.

THERMOCHEMICAL CYCLE OF AMMONIA PRODUCTION

As an alternative process for Ammonia production, a process employing the thermochemical cycle has been developed. The system consists of two circulated processes: reduction (nitrogen activation) and steam-hydrolysis (Ammonia formation). Both reactions are summarised as follows:

$Al_2O_3 + 3C + N_2 \rightarrow 2\ AlN + 3\ CO$

$\Delta H^{\circ}25\ ^{\circ}C = 708.1$ kJ/mol

$2AlN + 3\ H_2O \rightarrow Al_2O_3 + 2\ NH_3$

$\Delta H^{\circ}25\ ^{\circ}C = -274.1$ kJ/mol

Ammonia has historically been largely utilised in agriculture as a vital component in the creation of fertilisers. It has been essential in raising crop yields and guaranteeing food security. On the other hand, Ammonia has garnered increasing attention as a sustainable energy source in recent years.

By 1900, agricultural scientists figured out that nitrogen was the key player and Ammonia could supply the nitrogen the soil needed. The world population was growing, and food crops needed to keep up.

The use of ammonia as a fuel for internal combustion engines has been around since at least 1935. A more extensive use of Ammonia as a fuel was undertaken on vehicles in Belgium in 1942. In this case, Ammonia vapour plus coal gas was burned in the engine.

RECENT DEVELOPMENTS

Over the past few decades, a renewed focus on Ammonia as a sustainable energy carrier has been driven primarily by the need to reduce greenhouse gas emissions and transition to cleaner energy sources. The discovery of efficient methods for producing Ammonia using renewable energy sources and advancements in storage and transportation technologies have been key drivers of recent developments in this field.

One significant recent development is the use of Ammonia as a potential hydrogen carrier. Ammonia has a higher energy density than hydrogen gas and can be more easily stored and transported. It can be converted back into hydrogen on demand, making it an attractive option for applications such as fuel cells and hydrogen-powered vehicles.

Another recent development in the Ammonia energy field is the advancement of direct Ammonia fuel cells. These fuel cells directly use Ammonia as a fuel, eliminating the need for a hydrogen-producing step. This technology has the potential to provide a more efficient and cost-effective way to generate electricity from Ammonia.

Recent developments in Ammonia as a sustainable energy carrier showcase its potential to contribute significantly to the transition towards a cleaner and more sustainable energy system. Ongoing research and technological advancements in this field will continue to accelerate the adoption of Ammonia as a key player in the renewable energy landscape.

AMMONIA IN THE SUSTAINABLE ENERGY LANDSCAPE

Ammonia has drawn interest in the field of sustainable energy because of its potential for use in a number of applications, including the creation of green hydrogen, the integration of renewable energy sources, and solving storage and transportation issues.
Renewable Energy Integration: Ammonia is becoming a more popular green fuel, and this trend is part of a larger global trend where there is an increasing urgency to address climate change and move toward sustainable energy sources.
In order to fulfil net zero emissions targets, countries and industries are searching for cleaner alternatives to traditional fossil fuels. To this end, new carbon-free fuels are required to decarbonise transportation, industry, electricity generation, and heating. Actually, the worldwide movement toward industry decarbonisation and the usage of Ammonia are complementary. Numerous industries, like transportation and heavy industry, are dependent on fossil fuels and have difficulty lowering their carbon impact. Green Ammonia is a possible substitute that offers a cleaner fuel option and helps lower greenhouse gas emissions for these industries.
Green Hydrogen Production: Ammonia cracking, preferably carried out at normal pressures, generates hydrogen from Ammonia breakdown over a catalyst at high temperatures. The majority of catalytic cracking occurs in the presence of a catalyst at temperatures lower than 698 K, with a higher efficiency of roughly 98–99%. Thermal reactions begin at temperatures higher than 773 K without the requirement for a catalyst.

STORAGE AND TRANSPORTATION CHALLENGES

Ammonia also offers an answer to the problems of renewable energy's delivery and storage. Waste results when the amount of electricity produced from renewable sources surpasses the immediate requirement. It can function as an energy storage medium by electrolysing surplus electricity to create Ammonia. Ammonia has a high energy density, making transportation and storage effective. Furthermore, existing Ammonia storage and transportation infrastructure in the chemical and agricultural industries can be reused for applications related to renewable energy.
Nevertheless, there are still obstacles to be solved in the field of sustainable energy while using Ammonia. The total energy efficiency of the Ammonia production process is a big challenge because electrolysis uses a lot of electricity. The goal of research and development is to increase the electrolysis process's efficiency and make it more commercially feasible. Ammonia is hazardous and needs to be handled carefully, along with infrastructure upgrades, to assure safety. This presents another obstacle to its safe handling and storage. Furthermore, it could be necessary to modernise the current Ammonia transportation infrastructure in order to satisfy the demands of the sustainable energy industry.

THE ROLE OF AMMONIA IN THE ENERGY TRANSITION

Ammonia has become a significant actor in the worldwide energy transition, mostly being recognised for its use in fertilisers and household cleaning products. It is a key component in the production of ammonium nitrate, a widely used nitrogen fertiliser. This process involves combining Ammonia with nitric acid to form ammonium nitrate, a nutrient-rich fertiliser that provides essential nitrogen to plants for healthy growth. Ammonia has gained attention as a flexible and environmentally friendly energy carrier with tremendous potential to transform the landscape of numerous sectors as countries step up their efforts to decarbonise and move towards sustainable energy sources. Because of its special qualities, it is a viable option to help integrate renewable energy, solve issues with energy storage, and function as a clean fuel in industries like power generation and transportation.

The role of Ammonia in the energy transition extends beyond its conventional applications. Ammonia (NH3) is composed of nitrogen and hydrogen, and its significance lies in its ability to store and transport hydrogen, a clean energy source, in a compact and manageable form. The production of "green Ammonia," generated using renewable energy in the synthesis process, aligns with sustainability goals and offers a pathway to a carbon-neutral energy economy.

The multifaceted role of Ammonia in the energy transition can be examined across several key dimensions.

AS A HYDROGEN CARRIER

Pure hydrogen storage and transit present difficulties mitigated by Ammonia's role as a hydrogen carrier. Hydrogen may be easily recovered from Ammonia by a procedure known as "Ammonia cracking," which offers a practical way to store and release hydrogen as needed.
"Ammonia cracking" or "Ammonia decomposition" is one of the essential steps that permits the use of Ammonia as a hydrogen carrier. In this process, Ammonia is broken down into components: nitrogen (N2) and hydrogen (H2). The equation represents the reaction:

$$2NH3 \rightarrow N2 + 3H2$$

Ammonia is thermally decomposed in this reaction to produce nitrogen and hydrogen gases. The released hydrogen can be utilised for various applications, including energy generation, fuel cells, and industrial processes. The utilisation of Ammonia as a hydrogen carrier offers a pragmatic approach to augment the feasibility and adaptability of hydrogen utilisation across many industries, hence promoting the progress of sustainable and clean energy systems. Because of its high hydrogen concentration (17.8% by weight), easy liquefaction at atmospheric pressure, and suitable temperature (around -33.34°C), Ammonia (NH_3) is a promising contender. Ammonia storage and transportation can be facilitated by utilising the current infrastructure.

ENERGY STORAGE

Ammonia can be used for energy storage as well as other green energy applications. An alternative to intermittent renewable energy sources like solar and wind power is available by storing and transporting extra energy through the Power-to-Ammonia process. Excess electricity from sporadic renewable energy sources, including solar and wind power, can be transformed into Ammonia, which can be transported, stored, and used as a flexible energy source.

KEY ASPECTS OF POWER-TO-AMMONIA (PTA)

1) Electrolysis to Hydrogen: Hydrogen is usually produced by electrolysing water as the first step in the PtA process. In this process, water is divided into hydrogen and oxygen using electricity. One of the most important intermediate products in the PtA process is the hydrogen produced during electrolysis.

2)Ammonia Synthesis: The next stage includes mixing the produced hydrogen with nitrogen to form Ammonia (NH3) through the Haber-Bosch process. The electrical energy is captured and stored in this stage as chemical bonds inside the Ammonia molecules.

3) Energy Storage: Liquid Ammonia is an effective means of transferring stored energy. Ammonia has advantages over direct electrical storage, including simpler transportability and a higher energy density. Ammonia can be stored in tanks; its energy is released through controlled decomposition as needed.

4)Transportation and Distribution: Because Ammonia is used as a fertiliser in agriculture, it has a well-established infrastructure for distribution, storage, and transportation. Its transport can be facilitated by modifying or repurposing existing logistical networks, which makes it a feasible solution for moving stored energy to various sites.

5) Versatile Energy Carrier: Ammonia can be utilised as a feedstock for a number of processes, such as fuel cells, power generation, and industrial operations. The capacity to release stored energy from Ammonia on demand offers a level of flexibility to the energy system, allowing for the integration of renewable sources without the limits of intermittency.

6) Decoupling Energy Production and Consumption: PtA facilitates the decoupling of energy production and consumption by offering a way to store excess energy produced during high renewable energy availability intervals for use during low availability intervals.

7) Grid Balancing: By storing excess energy during periods of low demand and releasing it during periods of peak demand, PtA can help with grid balancing and make the electricity system more dependable and stable. Dealing with the intermittent nature of renewable energy sources is feasible using the Power-to-Ammonia process. It offers a practical choice for extensive energy storage, transportation, and various other uses.

CLEAN FUEL IN TRANSPORTATION

Ammonia's application as a fuel in the transportation sector is gaining momentum. Green Ammonia has the potential to displace conventional fossil fuels in a variety of transportation applications, thereby reducing greenhouse gas emissions, as it is a carbon-free fuel.
Being carbon-free, green Ammonia is marketed as a potential answer to the problems with traditional transportation fuels and their negative environmental effects. Carbon dioxide and other dangerous pollutants are released during the combustion of fossil fuels, in contrast to green Ammonia, which yields nitrogen and water vapour. Green Ammonia is positioned as a major contributor in efforts to decarbonise the transportation industry because of this feature.
It is an appealing option for managing emissions on both short- and long-distance travel because of its versatility. Green Ammonia has a lot of potential for the transportation sector, but there are still obstacles to overcome as coordinated efforts are needed in the areas of supply chain establishment, engine changes, and infrastructure development. Industry players, legislators, and researchers may work together to address these obstacles to build a strong ecosystem for the broad use of green Ammonia in transportation.

The adaptability of green Ammonia to different forms of transportation is one of its unique characteristics. Green Ammonia may be effectively integrated into varied transportation applications, from maritime ships to heavy-duty vehicles and buses.

The importance of green fuels in reaching sustainability goals is becoming more widely acknowledged globally. Consequently, the integration of green Ammonia into international transportation frameworks is becoming increasingly important.
An important turning point towards ecologically conscious and sustainable mobility is the growing use of green Ammonia as a carbon-free fuel in the transportation industry. Green Ammonia holds the possibility of revolutionising vehicle power and helping to create a cleaner and greener transportation future via continued breakthroughs, cooperative efforts, and a commitment to mitigating climate change.

POWER GENERATION

The capacity of Ammonia to promote clean combustion is one of its most notable qualities in the production of electricity. In contrast to fossil fuels emitting greenhouse gases and particulate matter, Ammonia burning is distinguished by its negligible environmental impact. This is in line with international initiatives to switch to more sustainable and clean energy sources. Ammonia can also be used as a fuel in power generation, especially in fuel cells and gas turbines. Instead of releasing carbon dioxide and other pollutants like traditional fossil fuels, its burning produces nitrogen and water.

POWER GENERATION CONT'D

1)Ammonia in Gas Turbines: One important use where Ammonia excels as a green fuel is in gas turbines. Byproducts of Ammonia combustion in petrol turbines are nitrogen and water; no carbon dioxide or other pollutants typically connected with burning traditional fossil fuels are released into the atmosphere. Because of this property, Ammonia is a more environmentally ideal option for gas turbine systems while generating power.

2)Fuel Cells: Fuel cell technology presents an equally attractive option for Ammonia. Ammonia has energy that can be extracted and used using fuel cells, which are known for their effectiveness and low environmental impact. Ammonia and oxygen undergo an electrochemical reaction during the process, producing water and nitrogen as byproducts and energy. This demonstrates Ammonia's potential as a sustainable and clean energy source in fuel cells.

The use of Ammonia in power generation not only solves environmental issues but also improves energy security and efficiency. Its use of cutting-edge technologies like fuel cells and gas turbines promotes more effective energy conversion, guaranteeing a steady and sustainable power source.

Global Ammonia use in power generation is greatly aided by international initiatives and policy frameworks. Cooperative efforts on a worldwide scale characterise Ammonia's path as a fuel for green power generation. To enhance the understanding of Ammonia's potential and address issues, nations, research institutes, and industry partners collaborate on projects and share knowledge. Global knowledge is accumulated through cooperative research programmes, international conferences, and technology-sharing platforms, among other initiatives.

The transformation of Ammonia from a traditional chemical constituent to a sustainable fuel for electricity production highlights the transformational potential of Ammonia in the energy sector. With ongoing improvements and increasing support worldwide, Ammonia has the potential to completely transform the way we produce energy by providing a sustainable and eco-friendly substitute for conventional fossil fuels.

Ammonia plays a dynamic and revolutionary function in the energy transition. Its capacity to deliver, store, and transport clean energy makes it a vital component in the search for carbon-neutral and sustainable energy systems. Ammonia has the potential to be a key component in determining the direction of a cleaner, more sustainable energy environment as long as research and technology developments are sustained.

POTENTIAL AND CHALLENGES: ENVIRONMENTAL IMPACT

1)EMISSION REDUCTION POTENTIAL: Ammonia has the potential to reduce greenhouse gas emissions and improve air quality. Ammonia combustion produces only water and nitrogen, which are environmentally benign products. However, the production of Ammonia requires a significant amount of energy, which can lead to increased greenhouse gas emissions if the energy is not generated from renewable sources. It is also important to note that the type of Ammonia produced depends on the feedstock or source of energy used which can either be from renewables or fossil fuels. Green Ammonia is produced without fossil fuels and relies on renewable energy sources. It combines hydrogen (derived from water) and nitrogen (from air) using renewable energy. Unlike traditional “brown Ammonia” that relies on fossil fuels for both hydrogen and energy, green Ammonia production emits significantly fewer greenhouse gases compared to brown Ammonia. Each tonne of brown Ammonia releases about 2 tonnes of greenhouse gas, whereas green Ammonia avoids this impact. Green Ammonia can revolutionise agriculture by serving as a fossil fuel-free fertiliser. The Kenya Nut Company, for instance, produces its green Ammonia on-site using solar power. This could help decarbonise the agricultural sector, where Ammonia is widely used as a fertiliser. There’s hope that green Ammonia could also be used as a clean fuel alternative, contributing to a more sustainable energy mix.

2)LIFE CYCLE ANALYSIS: A life cycle analysis evaluates the environmental impact of a product or process from cradle to grave. It considers all stages, including raw material extraction, production, use, and disposal. For Ammonia, the LCA helps us understand its overall sustainability and identify areas for improvement Historically, Ammonia production relied on fossil fuels (natural gas) for both hydrogen and energy. This process emits significant greenhouse gases. In contrast, green Ammonia production uses renewable energy sources (such as wind or solar) to generate hydrogen and nitrogen. It significantly reduces carbon emissions.

KEY ASPECTS OF AMMONIA LCA

A) Energy Use: LCA tracks energy consumption at every stage, from raw material extraction to Ammonia plant gates. Green Ammonia's energy source (renewable vs. fossil fuels) impacts its overall environmental footprint.
B) Emissions: LCA assesses emissions (such as greenhouse gases) associated with Ammonia production. Green Ammonia emits fewer greenhouse gases compared to brown Ammonia.
C) Nitrogen Pollution: Ammonia is nitrogen-based, and its widespread use could impact the nitrogen cycle and contribute to nitrogen pollution. Proper engineering precautions are essential.
Transport and Spills: Using Ammonia for fuel or hydrogen transport may contribute to nitrogen pollution. Spills of Ammonia (as a shipping fuel, for example) could harm ecosystems.
D) Decarbonisation Efforts: Strategies include integrating carbon capture and sustainable hydrogen production via water electrolysis.

TECHNICAL CHALLENGES Production Efficiency

Haber-Bosch Process: The conventional method for Ammonia production is the Haber-Bosch process. While effective, it has drawbacks such as high greenhouse gas emissions (over 2.16 kgCO_2-eq/kg NH_3) and energy-intensive conditions (high temperature and pressure).
Green Ammonia: Sustainable hydrogen production methods, like water electrolysis coupled with renewable energy (wind or solar), are promising for green Ammonia synthesis. However, water electrolysis requires large volumes of pretreated water (233.6 million tonnes/yr for 1 tonne of Ammonia).

INFRASTRUCTURE DEVELOPMENT

Establishing a robust infrastructure for Ammonia production, storage, and transport is essential. Existing Ammonia infrastructure (used primarily for fertilisers) can be repurposed for energy applications. Developing safe and efficient pipelines, storage tanks, and distribution networks for Ammonia is critical.

ECONOMIC CONSIDERATIONS

Cost Competitiveness: Green Ammonia production costs depend on the energy source (renewable vs. fossil fuels) and technology. While green Ammonia may have higher upfront costs, its long-term benefits (reduced emissions and energy security) make it competitive. Achieving economies of scale and technological advancements will drive down costs.
Investment and Funding: Investment in research, development, and commercialisation of green Ammonia technologies is crucial. Public-private partnerships, government incentives, and international collaborations can accelerate progress. Attracting private investment and venture capital to support Ammonia projects is essential.

A chart of selected countries with Ammonia projects as curated by authors

CASE STUDIES: GLOBAL INITIATIVES

According to market research, the green Ammonia market was valued at $97.8 million globally in 2023 and is expected to grow significantly over the next several years, with a target of $4,517.6 million by 2030.

Some notable projects have been established in the green hydrogen and Ammonia sector over the last couple of years. Below, we highlight some of these notable projects worldwide that are actively involved in green Ammonia projects

A) REDDAP project, Denmark: REDDAP is short for Renewable Dynamic Distributed Ammonia Plant. The plant will harness renewable energy sources such as wind and solar to produce hydrogen through an electrolysis unit, which will then be converted to Ammonia.
B) Orsted Green Ammonia Project, The Netherlands: The project aims to produce Ammonia by substituting renewable hydrogen for fossil hydrogen in the process, potentially reducing annual CO2 emissions by over 100,000 tons, or the equivalent of taking 50,000 conventional automobiles off the road.
C) Plug Power Green Hydrogen and Ammonia Production Facility, Finland: With 1GW of electrolysers, this station is anticipated to produce up to 700 kt of green Ammonia annually and 85TPD of liquid green hydrogen annually.
D) Iverson eFuel Ammonia project, Norway: The plant is expected to generate about 200,000 tons of green Ammonia a year using green electricity derived from renewable hydropower sources. Production is expected to begin in 2028.
E) Yara Ammonia plant, Norway: By substituting renewable energy for fossil fuels, CO2 emissions will be cut by about 41,000 tons annually. With the hydrogen produced by the plant, 20,500 tonnes of Ammonia may be produced annually. This Ammonia can then be converted into 60,000–80,000 tonnes of green, fossil-free mineral fertiliser.
F) OM Green Ammonia Project, Oman: The facility is expected to produce 1.2 million tonnes of green Ammonia annually by mid-2025.
G) AMAN Project, Mauritania: When the AMAN project is completed, with about 30GW of hybrid wind and solar energy it will produce 10 million tons of green Ammonia and green hydrogen annually.
H) Suez Canal Economic Zone Green Ammonia Project, Egypt: The first phase will cost roughly $710 million and will create 20,000 tons of green hydrogen and 100,000 tons of green Ammonia between 2023 and 2025. With projected investments of over $7,147 billion, the production capacity in the second phase between 2025 and 2029 seeks to generate 200,000 tons of green hydrogen and million tons of green Ammonia. The initial phase of the project, which will be located in the Sokhna integrated Zone, will occupy 600,000 square meters. This would enable the production of 1,100 million tons of green Ammonia and 220,000 tons of green hydrogen.

GLOBAL INITIATIVES CONT'D

H2-Hub (TM) Gladstone, Australia: Up to 5,000 tonnes of Ammonia per day are to be delivered by the proposal, which integrates up to 3GW in an electrolyser plant. H2U hopes to start production in Gladstone, Queensland, by 2025 after receiving approvals by 2023.

Project GERI, Australia: With a combined 4GW of solar and wind power, the project intends to grow to a 1.5GW electrolyser capacity and go commercial.

HØST PtX Esbjerg Green Ammonia Plant, Denmark: Significant progress to decarbonise infrastructure and agriculture can be achieved via this plant. The plant aims to produce 600,000 tonnes of green Ammonia annually. Furthermore, the plant's surplus heat will heat a third of the city's homes.

FUTURE OUTLOOK: TECHNOLOGICAL ADVANCEMENTS: RESEARCH AND DEVELOPMENT

Ammonia plays a crucial role in global agricultural systems as it serves as the starting point for mineral nitrogen fertilisers, bridging the gap between atmospheric nitrogen and the food we consume. Underlisted are some notable developments:

SUSTAINABLE PRODUCTION

• Renewable Sources: Researchers are actively exploring ways to produce Ammonia from renewable sources, such as green hydrogen. This ensures sustainability and reduces reliance on fossil fuels.
• Efficiency Improvements: Ongoing efforts focus on enhancing Ammonia synthesis efficiency. By optimising the production process, we can achieve higher yields with fewer resources.
• Cost Reduction: Innovations aim to reduce production costs, making Ammonia more accessible and economically viable.

CLEANER COMBUSTION AND CONVERSION

•Fuel Potential: While Ammonia is primarily used in agriculture and industry, there is growing interest in using it as a clean fuel. Technological developments are improving combustion and conversion processes, making Ammonia a more efficient and environmentally friendly option.

ROADMAP FOR THE FUTURE

According to the IEA's Ammonia Technology Roadmap, there are three possible futures for Ammonia production:

1) Stated Policies Scenario: The industry follows current trends but falls short of a sustainable trajectory in this scenario. In this scenario, the market dynamics and current policies essentially drive the Ammonia production industry to remain on its current track. Although efficiency and carbon reduction may see small but steady gains, total progress towards sustainability is not very great. It is possible that the industry may not be able to reach a fully sustainable trajectory and that emissions will continue to be higher than in more aggressive scenarios. Some salient features are a slow shift to greener industrial techniques, a limited uptake of renewable energy sources, and incremental advancements in technology. But without major market incentives or governmental changes, change comes slowly, and the business would find it difficult to reach environmental standards.

2) Sustainable Development Scenario: Here, the sector adopts technologies and policies aligned with the goals of the Paris Agreement. With the sector implementing technology and policies in line with the objectives of the Paris Agreement, this trend reflects a more proactive approach to sustainability. In this case, there is a deliberate attempt to lessen the environmental impact of Ammonia manufacturing by decarbonising it.
The extensive use of renewable energy sources, improved energy efficiency, and the application of carbon capture and storage (CCS) technology are important characteristics. Policy frameworks encourage investment and innovation in low-carbon Ammonia manufacturing techniques, accelerating the shift to more environmentally friendly technologies. Even while there are still issues with access to cheap renewable energy and the scalability of new technologies, the industry is making remarkable progress in cutting emissions and attaining higher sustainability.

3) Net Zero Emissions by 2050 Scenario: This trajectory, which aims to achieve net-zero emissions worldwide by 2050, is the most ambitious vision for the future of Ammonia production. In this case, the industry experiences a dramatic upheaval as it quickly moves towards carbon-negative or carbon-neutral production techniques.
The broad application of cutting-edge technologies, such as electrolysis, green hydrogen production, and Ammonia synthesis from renewable sources, is crucial. The sector maximises resource efficiency and minimises waste by adhering to the principles of the circular economy. Unprecedented degrees of cooperation, innovation, and investment are needed along the whole value chain to achieve net-zero emissions. Strong decarbonisation incentives and assistance for creating and applying cutting-edge technology are offered via policy frameworks. The potential benefits in terms of mitigating climate change and environmental stewardship are enormous, despite the formidable challenges that lie ahead, including high upfront prices and technological obstacles.

POLICY AND REGULATORY LANDSCAPE: INCENTIVES AND SUPPORT

Green Ammonia is becoming more feasible due to a convergence of the private sector and regulatory support. The IMO has introduced regulations to restrict greenhouse gas emissions from the maritime sector, and they include strict goals for lowering carbon dioxide (CO_2) emissions. For instance, the 2023 IMO GHG Strategy calls for a reduction in the carbon intensity of international shipping by at least 40% by 2030, with the goal of lowering CO_2 emissions per transport operation on average. Green Ammonia, a carbon-neutral fuel, is a viable way to decarbonise maritime transportation, in line with the IMO's goals of minimising the environmental effect of shipping activities. In an endeavour to become carbon neutral by 2050, the European Union (EU) has laid out a detailed plan for increasing the production and use of hydrogen. The EU's hydrogen strategy includes green Ammonia as a key component, aiming to assist in establishing infrastructure and capacity for renewable hydrogen generation to ease its integration into different economic sectors

Countries are also making movements. As an example, Japan has outlined ambitious plans to become a global leader in hydrogen energy, aiming to establish a hydrogen-based society by promoting hydrogen production, distribution, and utilisation. A vital part of Japan's hydrogen strategy is green Ammonia, which is created from renewable energy sources and provides a clean, sustainable substitute for conventional fossil fuels in a number of applications, such as power generation, transportation, and manufacturing.
Private companies, including energy producers, industrial manufacturers, and technology developers (e.g. Siemens Energy, ThyssenKrupp AG, ITM Power, YARA International etc.), are increasingly investing in green Ammonia production technologies and infrastructure. These investments are driven by environmental considerations and the potential economic opportunities of supplying clean energy carriers to domestic and international markets.

CONCLUSION

Ammonia is becoming more widely known for its ability to reduce CO2 emissions and ease the transition to sustainable energy systems due to its nitrogen and hydrogen composition. It provides dense storage, ease of processing, and environmental safety as a hydrogen transporter. Ammonia is a promising alternative for producing sustainable energy, particularly in isolated locations, due to its ability to replace conventional fuels. Current research focuses on the flexible use of Ammonia in a variety of industries by using it as a fuel in direct Ammonia fuel cells and for the creation of green hydrogen. Research and development initiatives are being used to address persistent challenges like energy efficiency and safety concerns.

The PtA process makes it possible to convert surplus electricity from sporadic renewable sources into Ammonia, providing a versatile energy source that can be used and stored. Ammonia is a viable choice for energy storage and transfer because of the existing agricultural infrastructure that makes distribution and transportation easier. Its adaptability also extends to power generation, where its clean combustion qualities support the creation of sustainable energy, and transportation, where green Ammonia offers a carbon-free substitute.

The industry's dynamism and decarbonisation potential is demonstrated by the significant rise the green Ammonia market is expected to see globally. Prominent global initiatives highlight the significance of technological progress and legislative backing in propelling the use of environmentally friendly Ammonia. Potential futures are outlined in the IEA's roadmap, which highlights the necessity of taking proactive steps to meet aggressive emissions reduction targets. Ammonia is becoming more and more important as nations work to achieve their sustainability targets in the shift to greener energy sources. Industry stakeholders must work together to solve issues and hasten the deployment of green Ammonia technologies. Funding for legislative frameworks, infrastructure development, and research is necessary to fully utilise Ammonia as a sustainable energy source. By working together, we can make the most of Ammonia's potential to create a greener, cleaner future for future generations.

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