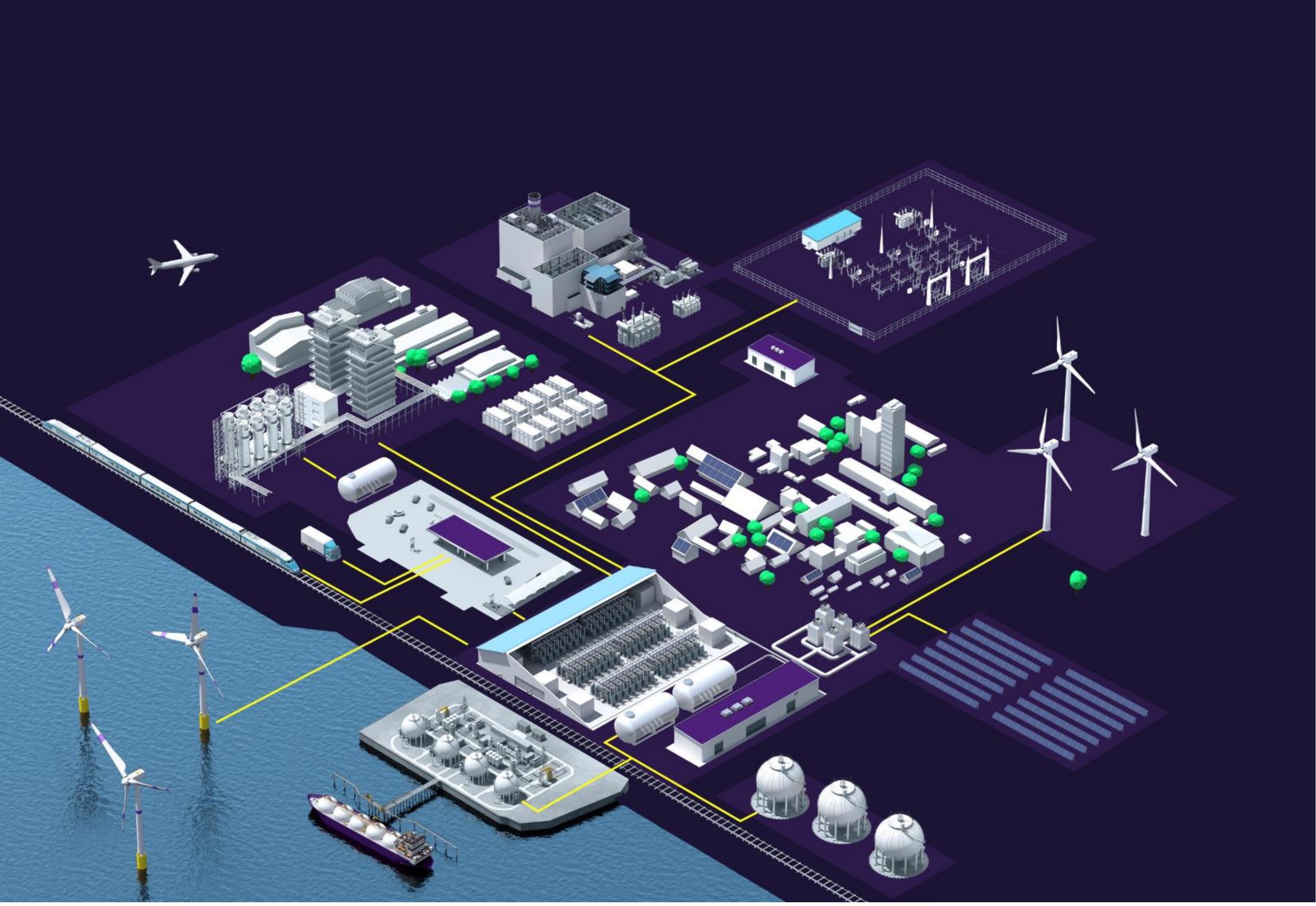


Power-to-X: A closer look at e-Ammonia

siemens-energy.com/electrolyzer

Contents

1. Introduction

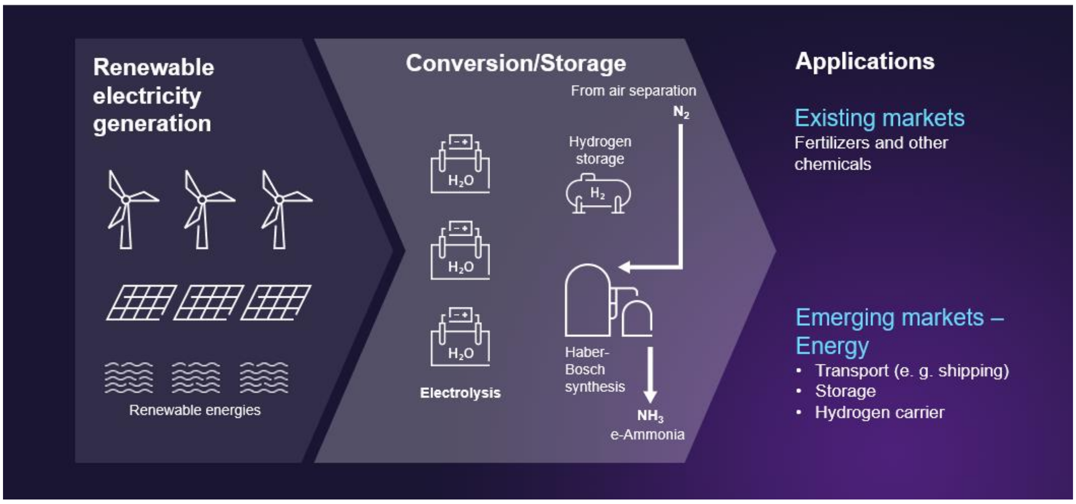
1.1 Transitioning towards net-zero systems

Humanity is at the beginning of an unprecedented, rapid transition towards sustainable systems. A sense of urgency is mounting to achieve a net-zero system by mid-century in order to limit global warming to well below 2 °C above preindustrial levels, as advised by the Intergovernmental Panel on Climate Change (IPCC). Already, nations are heeding this warning, signing net-zero targets into law, and mobilizing a significant push for deep decarbonization.

Achieving the required systemic transformation requires considering a range of technologies. One highly relevant technology for decarbonizing several sectors is e-Ammonia. E-Ammonia is a carbon-free chemical and fuel made from renewable electricity, water, and air that can be rapidly deployed at scale, building on a century of industrial ammonia infrastructure and expertise.

E-Ammonia is relevant for decarbonizing the existing ammonia market– a vast market worth tens of billions of euro and growing – as well as for emerging applications in decarbonizing parts of the energy sector, including shipping, large scale energy storage, distributed power generation and the bulk delivery of hydrogen. The significant advantage of e-Ammonia as an energy vector is the low cost of storage and transport, especially when compared to green hydrogen.

Based on both these large existing and emerging markets, e-Ammonia is a crucial technology in the transition to net-zero and thus warrants a closer look.



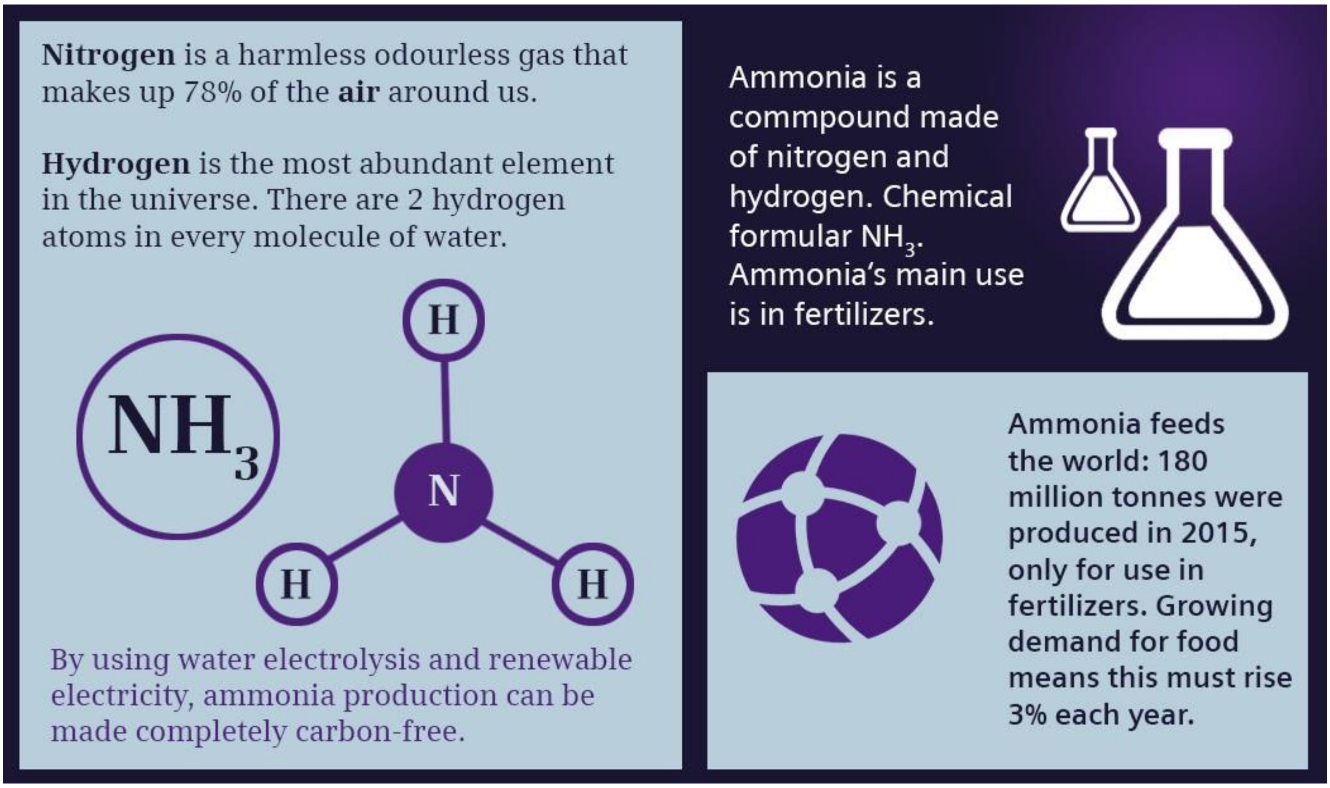
1.2 What is e-Ammonia?

Ammonia is a compound made of nitrogen and hydrogen with the chemical formula NH_3. Over 180 million tons of ammonia are already produced annually for various uses, including agricultural fertilizer, refrigeration, pharmaceuticals, textiles, and explosives. Ammonia is produced today using fossil fuel feedstocks and energy. **E-Ammonia**, also called green ammonia, is chemically the same compound; however, it is differentiated from traditional ammonia by virtue of its carbon-free method of production.

E-Ammonia is made from three simple inputs: water, air, and renewable electricity. First, hydrogen is generated from water using electrolysis (**green hydrogen**) and nitrogen is separated from air. Second, these feedstocks of hydrogen and nitrogen are combined in the century-old Haber-Bosch synthesis process to make ammonia. In the production of e-Ammonia, all processes are driven by renewable electricity, and thus there are no CO_2 emissions.

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3$$

Traditional ammonia production (i.e. “grey” or “brown” ammonia) uses natural gas or coal to provide both the hydrogen feedstock as well as the energy to power the Haber-Bosch synthesis process. As a result, traditional ammonia production releases almost 1.8% of global CO_2 emissions, making ammonia production one of the most carbon emitting industries in the world.[1] Fossil-fuel derived ammonia is produced at industrial scales in over 60 countries, including China, India, Russia, USA,Trinidad & Tobago, Indonesia, and Saudi Arabia.



1.3 E-Ammonia can be made at large-scale

Ammonia Making e-Ammonia is technologically feasible today using electrolysis of water, nitrogen separation from air, and existing Haber-Bosch synthesis technology. To demonstrate this, Siemens Energy designed and built the world’s first roundtrip e-Ammonia demonstration plant at the Rutherford Appleton Laboratory in the UK.

A first step in industrial e-Ammonia production is to add electrolysis capacity at existing fossil-fuelbased ammonia plants in low percentages. This stepping-stone can be beneficial for increasing familiarity with the e-Ammonia process and reducing CO_2 emissions of existing assets by displacing part of the fossil fuel hydrogen with green hydrogen. The scale of this green hydrogen production would not necessarily be small, as traditional Haber-Bosch synthesis plants are very large. Today, industrial ammonia production plants average 500 – 1,500 metric tons per day (MTPD) of ammonia, with the largest plants achieving over 3,500 MTPD. As an example of the large-scale nature of ammonia, replacing just 200 MPTD of this production with green hydrogen would require 150 - 200 MW of renewable electricity resources paired with similar sized electrolysis, assuming 50% capacity factor.[2]

As a next step, new e-Ammonia plants will be built with large renewable energy resources. A challenge with entirely e-Ammonia production is the process flexibility needed to manage variable renewable energy sources, such as solar and wind. Today, Haber-Bosch plants are optimized for continuous operation based on fossil fuel feedstock, and therefore operate with limited flexibility. Risks to flexible operation include reduced catalyst and equipment lifetime due to thermal

1 The Royal Society. (2020). Ammonia: zero-carbon fertilizer, fuel and energy store. London.

2 Assuming an electricity input of 9-12 MWh/tonne e-NH3 from calculations based on

cycling and decreased production efficiency. A solution that could be implemented today to manage intermittent renewable energy feedstock with an inflexible Haber-Bosch process would be to use a large hydrogen storage buffer. With this design, there would always be constant feedstock for the Haber-Bosch process. A better and more cost-effective solution would involve optimizing the Haber-Bosch process to vary output in line with the renewable energy input. This turn-down capability can likely be achieved through various plant design and operation techniques.

Finally, new technologies for e-Ammonia synthesis, such as lower pressure, lower temperature, or electrochemical synthesis are still in lab-scale research phases. Near-term e-Ammonia production facilities will likely use Haber-Bosch synthesis with some form of flexibility management.

1 Siemens Energy e-Ammonia demonstrator at Rutherford Appleton Laboratory in Oxfordshire, UK. Picture courtesy of the Science and Technology Facilities Council, UK.

1.4 Ammonia health and safety considerations

Ammonia is safely handled in many industrial and agricultural environments around the world today. There are over 10,000 ammonia storage sites in the USA alone, including in ports and agricultural locations.[1] While safe bulk ammonia storage and transport exist today, ammonia does have corrosive and toxic characteristics that warrant careful health and environmental considerations.

Ammonia is a pungent, colorless gas at ambient pressure and temperature. It is commonly stored in liquid form either at modest pressures (10 – 15 bar) or refrigerated to -33°C at ambient pressure. Ammonia is readily detected by smell at concentrations below levels that are harmful to health, with a characteristic smell found in common household cleaners and smelling salts. In nature, ammonia is produced from bacterial processes and when plants, animals, and animal wastes decay.
Regarding environmental impact, ammonia itself is not a greenhouse gas, however it does decompose to NO_x (a potent

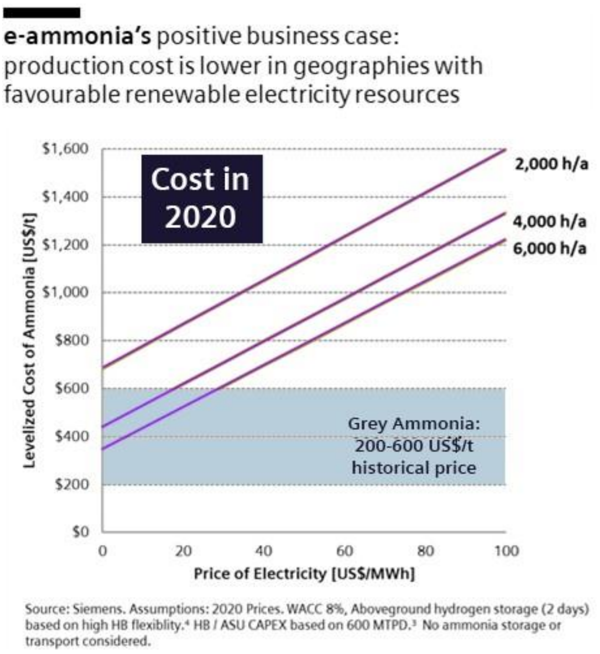
greenhouse gas) in the atmosphere. Only a fraction of the ammonia used in agriculture is taken up into food and the remainder runs into water, soil, and air. Therefore, current agricultural practices require management of ammonia release to the environment. Emissions can be completely controlled when using ammonia for energy purposes. Fundamentally, generating energy from ammonia involves converting ammonia back into nitrogen and water. Fortunately, existing post-combustion technology, such as selective catalytic reduction (SCR), can be used to reduce NO_x to nitrogen and water in the case that some NO_x emissions are generated from an ammonia combustion system. Moreover, the existing SCR process, which is often used for scrubbing NO_x emissions from diesel engines, actually utilizes ammonia (or derivatives such as urea) as the chemical reducing agent

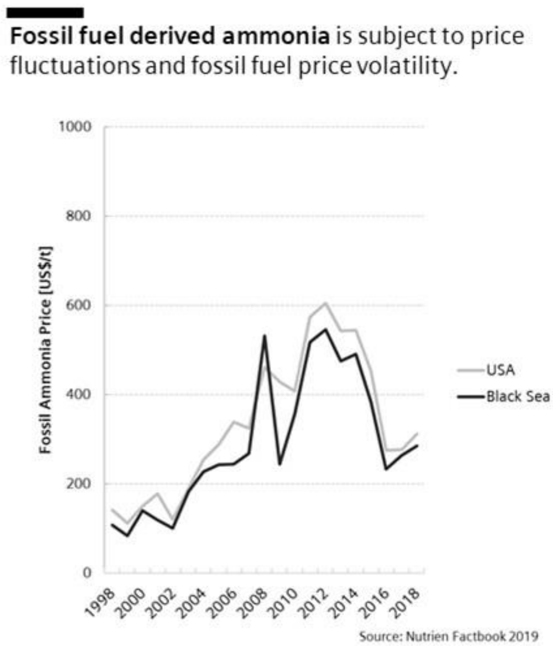
2. Economic feasibility and drivers

2.1 Production cost of e-Ammonia

The dominant factor in the production cost of e-Ammonia is the cost and availability of renewable electricity. Over 90% of the renewable electricity required for e-Ammonia synthesis is consumed in the production of green hydrogen via electrolysis. The Haber-Bosch and nitrogen separation processes account for approximately 7% and 1% of electricity consumption, respectively.[3] The availability of renewable energy (i.e. capacity factor) affects asset utilization as well as the quantity of hydrogen buffering required for Haber-Bosch flexibility management. Other factors affecting the production cost of e-Ammonia are the cost and efficiency of electrolysis as well as the cost of capital. Beyond production cost, the storage and transport costs for e-Ammonia delivery to a customer are relatively low, in contrast to many methods of transporting hydrogen.

Renewable electricity and electrolysis are forecasted to continue experiencing cost reductions over the next 5 to 10 years. Solar and wind technologies have well-established technology experience curves and the specific investment cost of electrolysis will be reduced by upscaling, improving the manufacturing process (automation) and/or substituting high-cost materials. Already today, e-Ammonia is approaching competitiveness with grey ammonia in regions with high capacity factors and low-cost renewable energy sources, such as Chile[4], Morocco, and Australia.





3 Assuming 8.4 MWh/t NH3 for green hydrogen (70% efficient), 0.6 MWh/t NH_3 for Haber-Bosch, and 0.1 MWh/t NH_3 for air separation. Nayak-Luke, R., Banares-Alcantara, R., & Wilkinson, I. (2018). "Green" Ammonia: Impact of Renewable Energy Intermittency on Plant Sizing and Levelized Cost of Ammonia. Industrial and Engineering Chemistry Research(57), 14607–14616. doi:10.1021/acs.iecr.8b02447

4 Armijo, J., & Philibert, C. (2020). Flexible production of green hydrogen and ammonia from variable solar and wind energy: Case study of Chile and Argentina. International Journal of Hydrogen Energy, 1541-1558. doi:10.1016/j.ijhydene.2019.11.028

2.2 Storage and transport of e-Ammonia

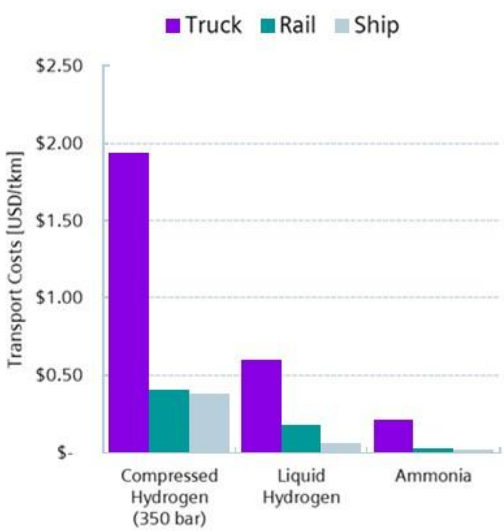
The significant advantage of ammonia as an energy vector is the low cost of storage and transport, especially when compared to hydrogen. Ammonia can be stored as a liquid via mild pressurization (10 bar at 25°C) or via refrigeration (-33°C at 1 bar). In comparison, hydrogen requires extremely low temperatures to liquefy (-253°C at 1 bar) or very high pressure to store at a comparable energy density (above 700 bar). Storing bulk hydrogen aboveground generally uses tanks at pressures up to 200 bar. However, this form of storage is over 50 times more expensive and 7 times more space-consuming than storing the equivalent hydrogen in the form of ammonia.[5] While some locations in the world have favorable geology for low-cost underground salt cavern storage of hydrogen, ammonia can be applied in a geographically independent context.

Transport of ammonia is well understood via pipeline, rail, truck, and ship, with roughly 20 million tons per year being exported and globally traded. Many ports around the world can load, unload, and store industrial scales of ammonia.[1] The transport cost of ammonia via ship is approximately 30 US$ per metric ton per 1,500 km.[6] This low cost of transport may justify the production cost differential between regions of favorable renewable electricity resources, such as Chile and Morocco, and markets such as Europe and Asia

Comparing fuels

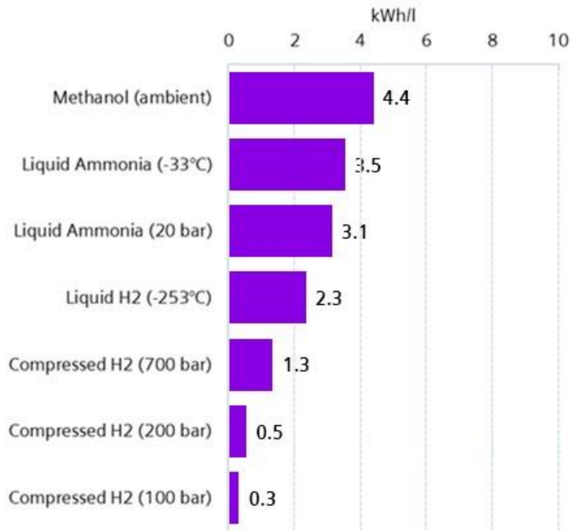
E-ammonia is cheaper to store and transport than hydrogen.

e-ammonia is cheaper to transport than e-hydrogen.



Source: CSIRO National Hydorgen Roadmap (2018)

e-ammonia and **e-methanol** are more energy dense than e-hydrogen.



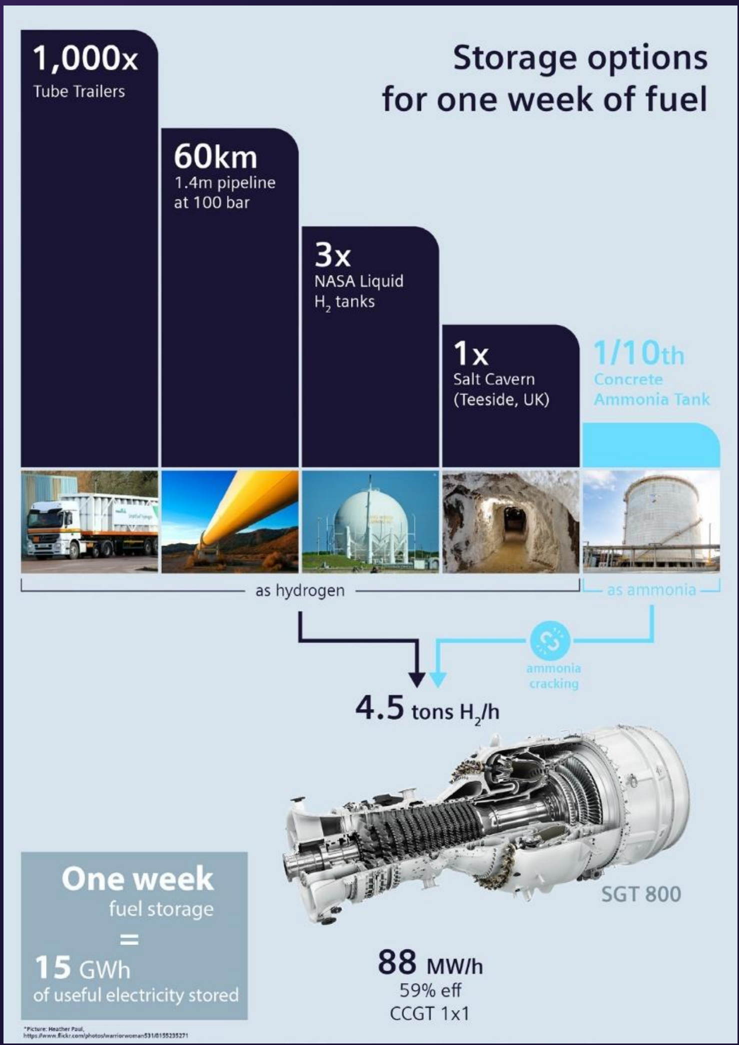
5 Hydrogen aboveground storage CAPEX 670 USD/kg H_2([6]) and ammonia 2 USD/kg NH_3 (11 USD/kg H_2)([17])

6 Bruce, S., Temminghoff, M., Hayward, J., Schmidt, E., Munnings, C., Palfreyman, D., & Hartley, P. (2018). National Hydrogen Roadmap. Commonwealth Scientific and Industrial Research (CSIRO).

Box 1: Ammonia is practical for large-scale energy storage

Ammonia has a key advantage in storage capability. Large-scale storage will become especially useful for ensuring reliability and dispatchable energy for net-zero national electricity grids. This has led to substantial interest in hydrogen gas turbine generation for seasonal grid balancing and mid to long-term electricity storage. Siemens Energy has substantial hydrogen compatibility in our gas turbine portfolio with a target of 100% H_2 compatibility across the portfolio by 2030. Research is ongoing in ammonia firing of gas turbines and ammonia/ hydrogen blends.

To highlight the differences in practical storage of large quantities of energy, take an 88 MW SGT-800 combined cycle gas turbine (CCGT) power plant operating at 59% fuel efficiency running on hydrogen. Storage options for one week of hydrogen fuel stored in the form of hydrogen is compared in the figure with one week of hydrogen fuel stored in the form of ammonia:



*Assumptions: Tube trailer = 800 kg H_2, Pipeline: 1.4 Diameter pipeline at 100 bar (12 ton H_2/km)[7], NASA Spherical Liquid Cryogenic Tank: 230 tons H_2, Teeside Salt Caverns[8] 810 tons (210,000 m^3 at 45 bar). 50,000 t ammonia storage tank[9]: single-wall refrigerated, concrete containment walls.

7 J. Andersson and S. Gronkvist, "Large-scale storage of hydrogen," International Journal of Hydrogen Energy, v. 44, 11901-11919, 2019.

8 E. Wolf. "Large-scale hydrogen energy storage," J. Garche (Ed.), Electrochemical energy storage for renewable sources and grid balancing, Elsevier, Amsterdam (2015), pp. 129-142

9 McDermott. QAFCO Ammonia Storage Tanks – Snamprogetti. https://www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks (Accessed May 05 2020).

3. Key markets

3.1 Existing market: fertilizers and other chemicals

Over 80% of ammonia produced today is used in the fertilizer sector. Ammonia is used directly as a fertilizer and as a feedstock for other chemical fertilizers, such as urea, ammonium nitrate, and other NPK combination fertilizers. The current ammonia fertilizer market consumes over 25 million metric tons per year of hydrogen. Thus, decarbonizing the existing ammonia market represents a large opportunity for e-Ammonia to significantly reduce global emissions.

3.2 Emerging markets: energy

Transport Fuel

E-Ammonia is increasingly viewed as a promising fuel for decarbonizing the shipping sector. Recent industry reports highlight ammonia's role in the future of shipping, including reports from DNV-GL[10], NYK[11], Maersk[12], Lloyd's Register[13], Korean Register[14], etc. Ammonia plays a key role in decarbonizing shipping in the UK Committee on Climate Change Net Zero report.[15] Favorable attributes of e-Ammonia for shipping fuel are the relative high energy density, zero carbon content, and the scalability of production to meet the global demand (especially compared to biofuels). Ship engine manufacturers, including MAN Energy Solutions, have already begun testing ammonia-fueled engines and are exploring concept designs for ammonia fueled ultra-large container ships.[16] As detailed in Section 1, existing post-combustion SCR technology can be used to reduce undesirable NO_x emissions should they arise from direct ammonia combustion engines. For other applications in transport sector such as long-haul trucking and aviation, other synthetic liquid fuels e.g. e-Methanol, e-Gasoline, or e-Kerosene might be the preferred options.

10 DNV-GL. (2019). Maritime Forecast to 2050: Energy Transition Outlook 2019.

11 NYK (2020) NYK Examines Concept of Using Ammonia as Marine Fuel. NYK Press Release. Jan 30 2020. Online.

12 Maersk (2019). Alcohol, Biomethane and Ammonia are the best-positioned fuels to reach zero net emissions. Maersk Press Release. 24 Oct 2019. Online.

13 Lloyd's Register (LR) & University Maritime Advisory Services (UMAS). (2019). Zero Emission Vessels (ZEV): Transition Pathways.

14 Korean Register (KR). (2019). Forecasting the Alternative Marine Fuel: Ammonia. KR.

15 Committee on Climate Change (CCC). (2019). Net Zero: The UK's contribution to stopping global warming. London.

16 16 MAN Energy Solutions. (2019). Engineering the future two-stroke green-ammonia engine. Copenhagen.

Long duration and long distance energy storage

Ammonia has relatively low storage and transport costs which makes it a very versatile energy vector, similar to present day fossil fuels. Ammonia may be useful for seasonal storage of energy for electricity and heating needs. As highlighted, hydrogen storage in salt caverns may be more favorable for seasonal energy storage in certain geographies, while ammonia offers a geographically independent solution.

Overall, the lower cost of storing and transporting ammonia compared to hydrogen may economically justify ammonia as a medium for trading energy between countries. For example, the IEA identified a cost advantage for Japan to import hydrogen in the form of ammonia from Australia rather than produce hydrogen using local renewable resources.[17] Similar economics may emerge in other geographies, including supply in the Middle East, North Africa, and Latin America paired with demand in parts of Asia and Europe.

Hydrogen carrier

E-Ammonia is cost effective method for storing and transporting green hydrogen, which may play a role in enabling green hydrogen. In applications that require hydrogen, ammonia can be decomposed, or "cracked," back into nitrogen and hydrogen to deliver hydrogen to the end-user. The technology for ammonia decomposition is mature; however, the required purity for some hydrogen applications, including PEM fuel cell vehicles, is less than 0.1 ppm residual ammonia. The technology for achieving this strict purity in a cost effective manner is still being developed. Some applications of hydrogen do not require such high purity, including alkaline fuel cells and gas turbines. Siemens gas turbines (SGT) will be 100% hydrogen compatible by 2030, and therefore, e-Ammonia may also be a useful hydrogen carrier for heating, industrial use, and combustion power systems.

3.3 Comparing e-Ammonia with other e-Fuels

The principal advantage of e-Ammonia is its zero carbon content. Its use as an energy vector is therefore supportive of net-zero systems without the upstream or downstream carbon capture required by carbon-containing alternatives.

A second advantage is e-Ammonia's practical and cost-effective energy density, which enables it to be a genuine alternative to fossil fuels for bulk and seasonal storage of energy and the global transportation of renewable energy. It is a practical hydrogen vector, too: ammonia is more energy dense by volume than liquid hydrogen as well as cheaper to store and transport, as liquid hydrogen requires 25%-40% of the energy of hydrogen to liquify it at -253 °C.[17] Ammonia can be readily cracked back into hydrogen, and thus provide a feasible and geology-independent bulk hydrogen supply chain for energy sectors already committed to hydrogen as a fuel (such as mobility and gas turbines). Ongoing research and development activities into the combustion of ammonia blends – and even direct ammonia combustion – offer a path to further efficiency gains and equipment cost reductions for the use of ammonia as an energy vector.

A third advantage is the technological maturity. E-Ammonia can be synthesized from widely abundant resources (renewable energy, air, water) using industrially mature processes. Because ammonia synthesis, storage, and transportation infrastructure already exists, e-Ammonia can be rapidly deployed as an energy vector at the scales required to make meaningful reductions to carbon emissions.

The main disadvantage of ammonia is its toxicity, as discussed above. This means ammonia is unlikely to become a consumer product, for example. However, the existence of a significant worldwide ammonia industry today provides strong evidence that the risks associated with ammonia use can be reduced to acceptable levels within an industrial setting through appropriate equipment, design, and control measures. A second disadvantage is the formation of NO_x emissions in combustion systems. As previously discussed, existing technology for NO_x scrubbing is already widely available and research and development is active in preventing NO_x formation in the combustion systems in the first place.

E-Ammonia has similar energy requirements for synthesis to other carbon-containing e-Fuels (e-Methanol, for example); as with other e-Fuels the synthesis energy requirement is dominated by the energy required to produce the hydrogen feedstock. Compared to carbon-based e-Fuels, e-Ammonia may be a cheaper energy carrier in the long term due to feedstock cost of nitrogen (N_2) compared to carbon dioxide (CO_2). In the near term, biogenic and industrial waste streams, are sources of low-cost CO_2 feedstock. However, in the long term, recovering CO_2 from the atmosphere via direct air capture (DAC) will be required for large-scale carbon-based e-Fuel production. The cost forecasts for DAC are uncertain, but atmospheric nitrogen has a fundamental advantage over atmospheric CO_2 because the concentration of nitrogen in the atmo-

17 IEA. (2019). The Future of Hydrogen: Seizing today's opportunities. International Energy Agency.

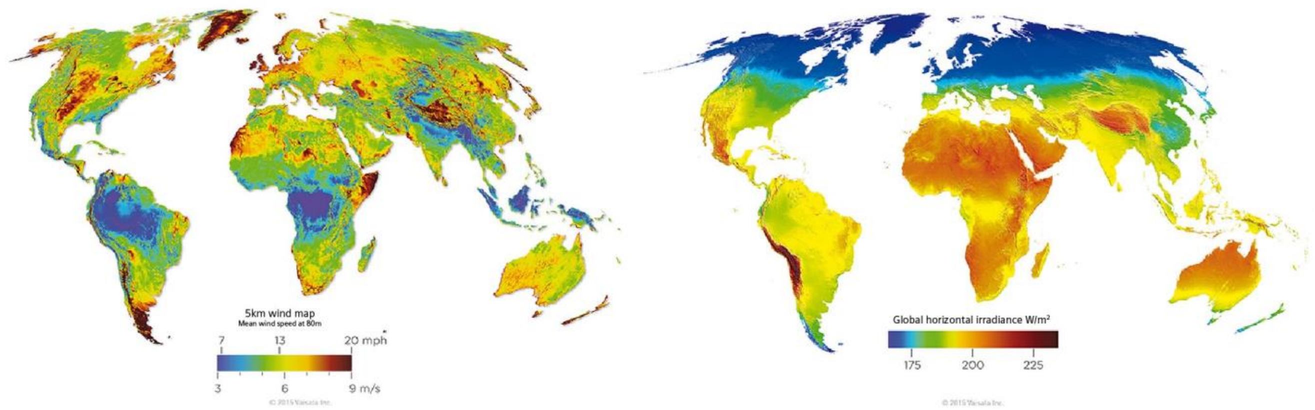
sphere is so much higher than the concentration of CO_2 (78% for N_2 compared to <0.5% for CO_2).Meanwhile, carbon-based e-Fuels have an advantage of higher compatibility with existing fossil fuel infrastructure (e.g. e-Fuels for automobiles and aviation), and are appropriate in applications where zero-carbon alternatives such as hydrogen and ammonia are difficult to deploy. Thus ammonia is being investigated, alongside carbon-based e-Fuels, as a practical, cost-effective energy carrier for net-zero systems

4. A closer look at e-Ammonia around the globe

4.1 Sustainable economic growth

E-Fuels, such as e-Ammonia, can play a role in supporting economic growth in different parts of the world where abundant, low-cost renewable resources offer a competitive advantage. The existing and emerging ammonia markets are an opportunity for economic and social improvement while contributing positively towards decarbonization. A few particularly strong candidates for production and export of e-Ammonia due to cheap and abundant wind and solar resources include Morocco, Australia, and parts of Latin America, such as Chile and Argentina.

There are many regions worldwide benefiting from the generation of power from renewable sources



Global wind map

Global solar map

Graphics from Tanja Siegel – independent-medien-design.de

4.2 E-Ammonia opportunities in existing markets

In some regions, e-Ammonia production can replace imports in the first instance. In Morocco, 2 million tons of ammonia are imported annually as a raw material[18] – or roughly US$600 million– for producing export quality fertilizers in combination with Morocco's phosphate resources. Similarly, Chile imported between US$100 - 200 million of ammonia per year from 2011-2016.[19] Local production of e-Ammonia in both geographies can meet domestic needs of ammonia for fertilizer and chemicals and eliminate reliance on imported ammonia.

In other regions, e-Ammonia represents an opportunity for decarbonization of existing assets. For example, while most of Latin America imports ammonia, Trinidad and Tobago is the world's leading exporter of ammonia, based on natural gas feedstock.[18] The addition of electrolysis from renewable electricity to existing plants represents an important opportunity for transitioning the industry towards more sustainable production. Decarbonization of existing ammonia plants with incremental electrolysis is already being investigated in Australia, another large producer of fossil-fuel derived ammonia.[20]

18 Nutrien Fact Book 2019. Nutrien LTD 2020.

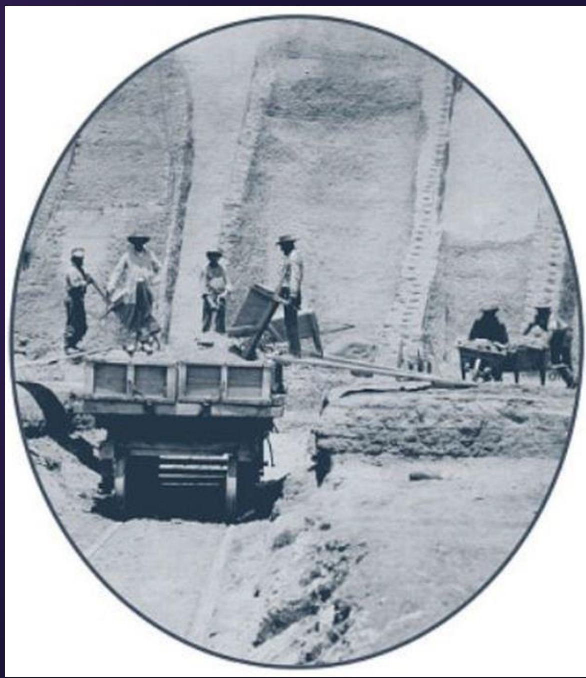
19 Datawheel, 2017. https://datachile.io. Chemical Product: Ammonia.

20 Australian Renewable Energy Agency (ARENA) 2020. Yara Pilbara Renewable Ammonia Feasibility Study. https://arena.gov.au/projects/yara-pilbara-renewable-Ammonia-feasibility-study/

E-Ammonia can also be exported overseas to various demand centers, including Asia and Europe. E-Hydrogen can be transported in the form of e-Ammonia and cracked back to green hydrogen at the end user. The Chilean government is already investigating potential methods for exporting green hydrogen to Japan and the Republic of Korea[21], research groups supported by the German government are investigating e-Ammonia from Morocco[22], and the Australian government is investigating method for delivering green hydrogen to Japan.[17,23]

Box 2: Bringing fertilizer production back to South America

Fertilizer production and export is an old industry in Chile and Peru, dating to the guano boom in the 19th century. Guano (dried excrement from birds and bats) was harvested and mined from the dry coast of South America for direct use as fertilizer and feedstock for explosives around the world. The invention of the Haber-Bosch process disrupted this Industry in the early 20th century. One hundred years later, the very same Haber-Bosch synthesis process presents the opportunity for these regions of Latin America to participate in global fertilizer production once again. There is also export potential to Asia for energy as well as supplying bunker fuel to various ports if e-Ammonia becomes a key fuel for international shipping. In particular, the Panama Canal sees substantial international shipping container traffic, as do ports in Brazil, Mexico, Colombia and other countries in Latin America.



Workers load guano onto a cart in 1865

4.3 A new wave of green industry

Industrial revolutions disrupt industries but also open new opportunities at the same time. For ammonia, the opportunity is large to expand the market into the energy sector with space for new producers. Regions with favorable renewable resources can lead in adopting e-Ammonia technology in this sustainable industrial revolution. Furthermore, e-Ammonia offers opportunity to further refine "raw materials" of sun and wind to establish local value-add industry of higher value chemicals that contribute to the decarbonization of the global value chain.

21 IRENA. (2019). Hydrogen: A Renewable Energy Perspective. International Renewable Energy Agency.

22 Wolfgang Eichhammer, Stella Oberle, Michael Händel, Inga Boie, Till Gnann, Martin Wietschel, Benjamin Lux; STUDY ON THE OPPORTUNITIES OF „POWER-TO-X" IN MOROCCO. Fraunhofer Institute for Systems and Innovation Research ISI. Feb 2019.

23 Australia's National Hydrogen Strategy 2019. COAG Energy Council, Commonwealth of Australia.

5. Conclusions

1. Ammonia production is a mature, global chemical industry that needs to decarbonize.
2. Producing e-Ammonia is feasible today with industrially mature technology.
3. Ammonia is energy dense, easy to store and transport, and has a global supply chain network.
4. E-Ammonia will be competitive in the near-term in geographies with low-cost renewable electricity and high capacity factors, such as Chile, Morocco, and Australia.
5. Existing markets for e-Ammonia include feedstock for fertilizers and other chemicals.
6. Future and emerging markets for e-Ammonia include shipping fuel, energy storage, and carrying hydrogen to end users.
7. Development is ongoing in using ammonia for power and other energy needs as well as delivering pure hydrogen to various consumers.

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