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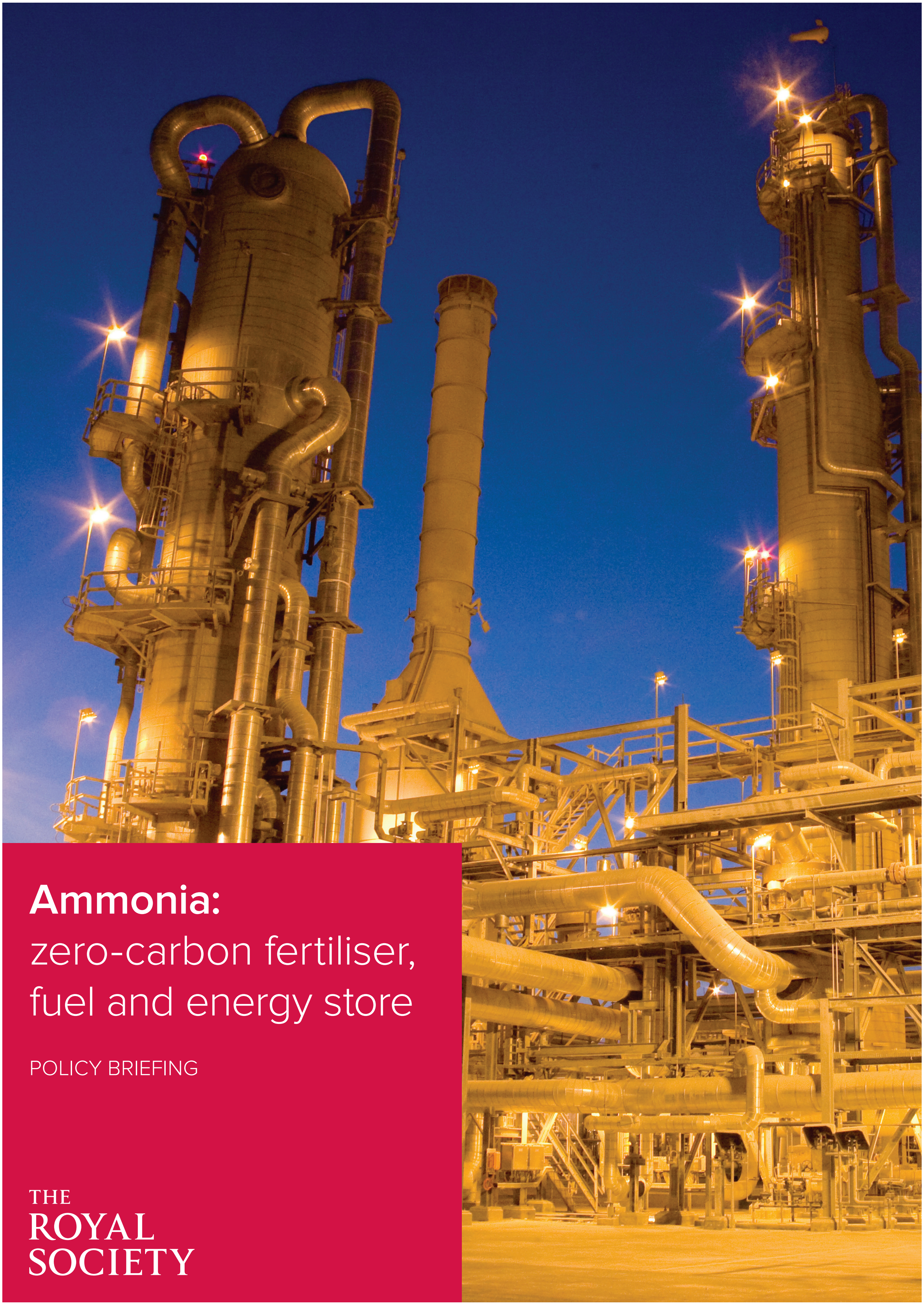

Ammonia:
zero-carbon fertiliser, fuel and energy store

POLICY BRIEFING

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Policy briefing

Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

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Ammonia: zero-carbon fertiliser,
fuel and energy store
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royalsociety.org/green-ammonia

Contents

Executive summary

The production of green ammonia has the capability to impact the transition towards zero-carbon.

Future zero-carbon energy scenarios are predicated on wind and solar energy taking prominent roles. Matching demand-driven energy provision with low-carbon energy security, from these intermittent sources, requires long-term sustainable energy storage.

This briefing considers the opportunities and challenges associated with the manufacture and future use of zero-carbon ammonia, which is referred to in this report as green ammonia.

The production of green ammonia has the capability to impact the transition towards zero-carbon through the decarbonisation of its current major use in fertiliser production. Perhaps as significantly, it has the following potential uses:

- As a medium to store and transport chemical energy, with the energy being released either by directly reacting with air or by the full or partial decomposition of ammonia to release hydrogen.
- As a transport fuel, by direct combustion in an engine or through chemical reaction with oxygen in the air in a fuel cell to produce electricity to power a motor.
- To store thermal energy through the absorption of water and through phase changes between material states (for example liquid to gas).

With its relatively high energy density of around 3 kWh/litre and existing global transportation and storage infrastructure, ammonia could form the basis of a new, integrated worldwide renewable energy storage and distribution solution. These features suggest ammonia could readily be a competitive option for transporting zero-carbon energy by road, rail, ship or pipeline.

Ammonia has been used as a fertiliser for over a century and has been of fundamental importance in providing sufficient food to feed our planet. Current ammonia manufacture is predominantly achieved through steam reforming of methane to produce hydrogen which is fed into ammonia synthesis via the Haber Bosch process. Ammonia production currently accounts for around 1.8% of global carbon dioxide emissions.

Decarbonisation options mainly target the production of hydrogen either by integrating carbon capture and storage or through the production of hydrogen via water electrolysis using sustainable electricity.

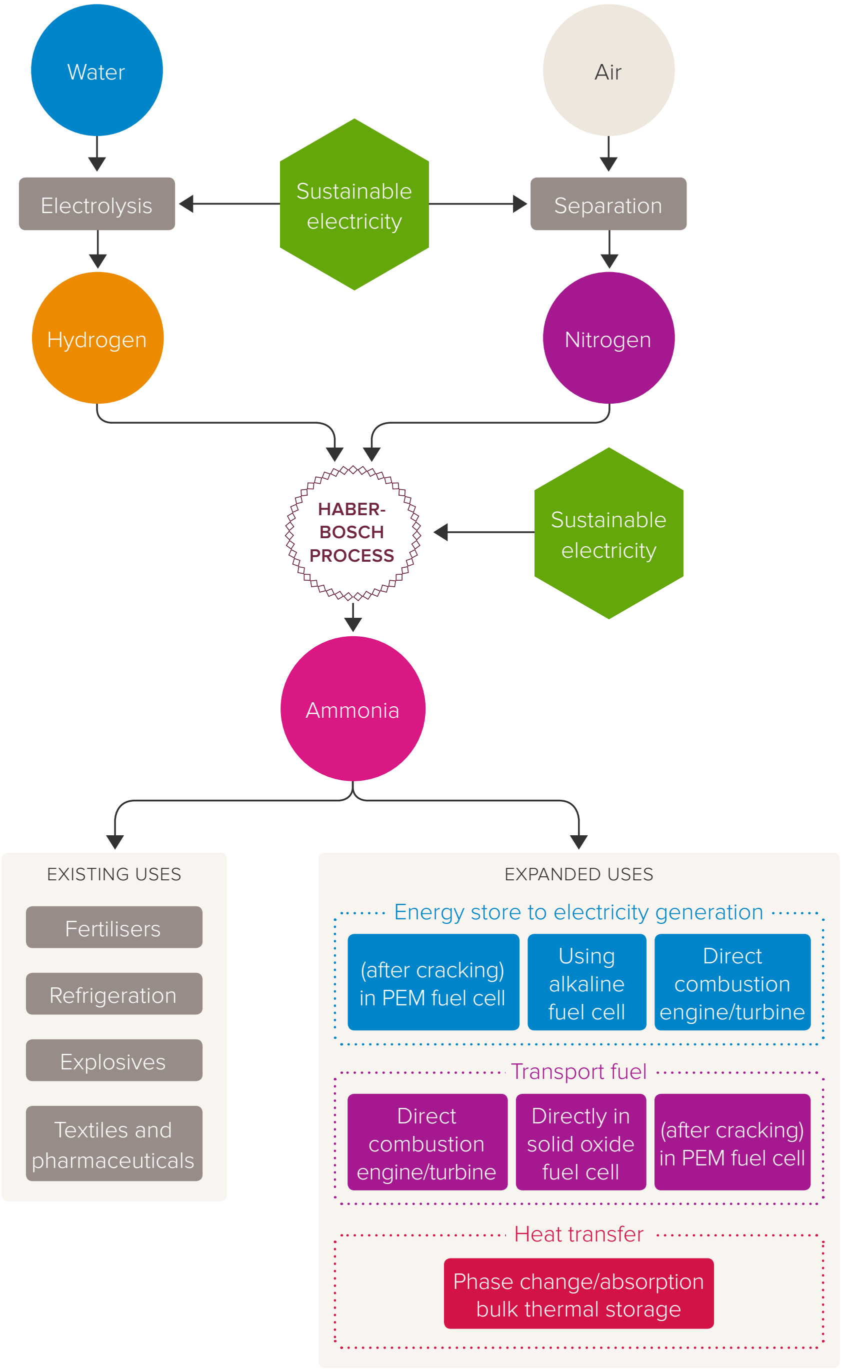
Ammonia use does present challenges. Human alteration of the global nitrogen cycle, mainly through the application of ammonia-based fertilisers, is a contributor to global declines in biodiversity, widespread air quality problems and greenhouse gas emissions across the world. New uses of ammonia, in the storage, transportation and utilisation of renewable energy, must therefore be decoupled from environmental impact, with particular emphasis on avoiding and effectively eliminating emissions of nitrogen oxides and ammonia release.

Finding affordable and effective solutions to all these challenges, demonstrating technical feasibility, developing the appropriate regulations and implementing safety procedures will be vital to open up more flexible routes on a global scale towards a low-carbon energy future.

Over the coming decades, ammonia has the potential to make a significant impact through enabling the transition away from our global dependence on fossil fuels and contributing, in substantial part, to the reduction of greenhouse gas emissions.

FIGURE 1

Green ammonia production and use.



Introduction

Current ammonia production generates 500 million tonnes of carbon dioxide.

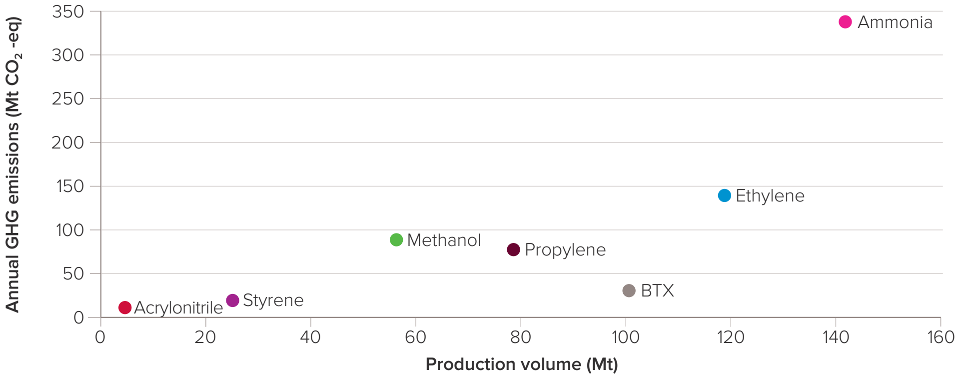
Ammonia has had a profound global impact since the discovery of its synthesis from hydrogen and nitrogen by Haber and Bosch in Germany at the beginning of the 20th century. The key role of ammonia today is as the basic feedstock for inorganic fertilisers that currently support food production for around half of the world's population[1].

Ammonia is an efficient refrigerant that has been used extensively since the 1930s in industrial cold stores, food processing industry applications and increasingly in large-scale air-conditioning. Ammonia is also the key component in the production of AdBlue for vehicle NO_x control, and in the pharmaceutical, textile and explosives industries.

Current global ammonia production is about 176 million tonnes per year and is predominantly achieved through the steam reforming of methane to produce hydrogen to feed into ammonia synthesis via the Haber Bosch process (see Chapter 1). Ammonia production is a highly energy intensive process consuming around 1.8% of global energy output each year (steam methane reforming accounts for over 80% of the energy required) and producing as a result about 500 million tonnes of carbon dioxide (about 1.8% of global carbon dioxide emissions)[2,3,4]. Ammonia synthesis is significantly the largest carbon dioxide emitting chemical industry process (Figure 2). Along with cement, steel and ethylene production, it is one of the 'big four' industrial processes where a decarbonisation plan must be developed and implemented to meet the net-zero carbon emissions target by 2050[5].

FIGURE 2

Greenhouse gas emissions for selected high production volume chemicals for 2010[4].



BTX – Benzene, Toluene, Xylene (aromatic chemicals). These 2010 numbers are the most recent published figures.
Note: Ammonia production in 2018 was 176Mt and generated around 500 million tonnes of carbon dioxide (per annum).

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1. Smil V. 2000 Enriching the Earth. ISBN 9780262194495.
2. Institute for Industrial Productivity. Industrial Efficiency Technology Database – Ammonia.
3. International Fertiliser Industry Association. 2009 Fertilisers, Climate Change and Enhancing Agricultural Productivity Sustainably. See https://www.fertilizer.org/Public/Stewardship/Publication_Detail.aspx?SEQN=4910&PUBKEY=0E80C30A-A407-49D2-86B5-0BAC566D3B26 (accessed 29 May 2019).
4. IEA, ICCA, DECHEMA. 2013 Technology Roadmap – Energy and GHG Reductions in the Chemical Industry via Catalytic Processes.
5. McKinsey & Company. 2018 Decarbonization of Industrial Sectors: the next Frontier. See https://www.mckinsey.com/~/media/mckinsey/business%20functions/sustainability/our%20insights/how%20industry%20can%20move%20toward%20a%20low%20carbon%20future/decarbonization-of-industrial-sectors-the-next-frontier.ashx (accessed 29 May 2019).

In addition to its established uses, ammonia can be applied as a flexible long-term energy carrier and zero-carbon fuel. In common with fossil fuels, ammonia is both a chemical energy store and a fuel, where energy is released by the breaking and making of chemical bonds. For ammonia (NH_3), the net energy gain arises from breaking nitrogen-hydrogen bonds which, together with oxygen, produces nitrogen and water. Importantly, this means that if sustainable energy is used to power the production of green ammonia, it can be made sustainably using only air (which is around 78% nitrogen) and water.

The energy storage properties of ammonia are fundamentally similar to those of methane. Methane has four carbon-hydrogen bonds that can be broken to release energy and ammonia has three nitrogen-hydrogen bonds that can be broken to release energy (Figure 3). The crucial difference is the central atom, where, when burnt, the carbon atom in methane produces carbon dioxide, whereas the nitrogen atom in ammonia results in nitrogen gas, N_2.

FIGURE 3

Structure of methane and ammonia.

Methane CH_4 Ammonia NH_3

At room temperature and atmospheric pressure, ammonia is a colourless, pungent gas. To store in bulk, it requires liquefaction either by compression to 10 times atmospheric pressure or chilling to -33°C. In this state, the energy density of ammonia is about 3 kWh/litre which is less than but comparable with fossil fuels (Figure 4).

Hydrogen by comparison is also a gas at atmospheric pressure and room temperature. However to store hydrogen at scale it must be compressed to around 350 to 700 times atmospheric pressure, or cryogenically cooled to -253°C. Consequently, the storage of hydrogen is more difficult, energy intensive and expensive than storing ammonia.

FIGURE 4

The volumetric energy density of a range of fuel options.

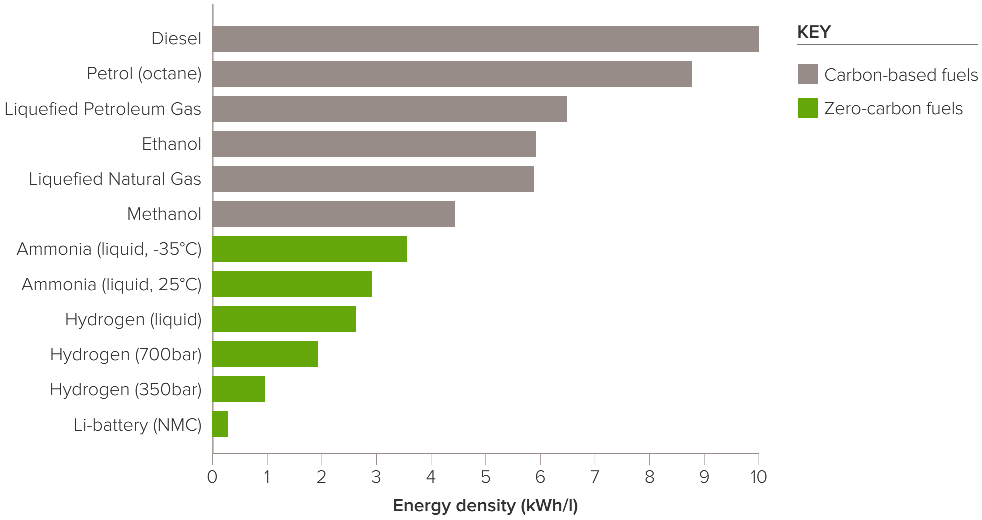
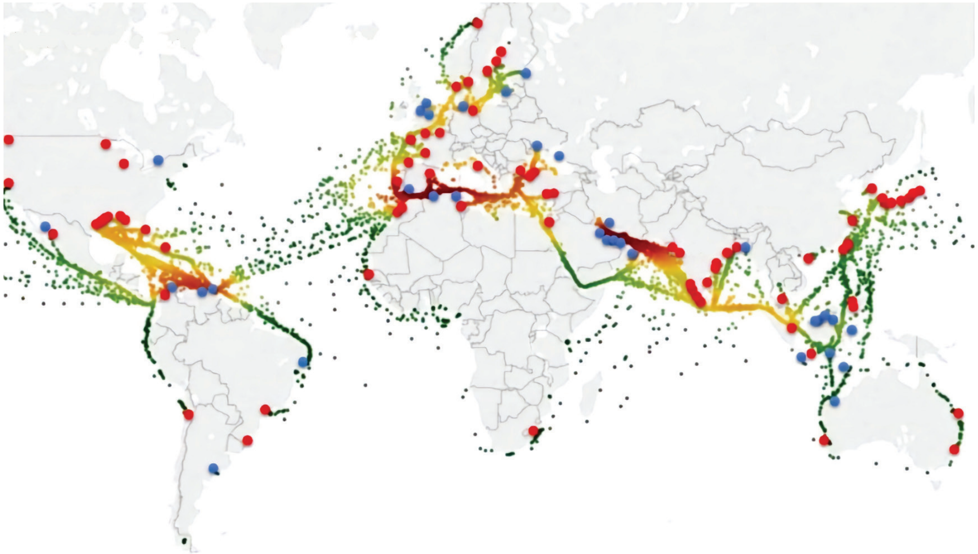


FIGURE 5

Ammonia shipping infrastructure, including a heat map of liquid ammonia carriers and existing ammonia port facilities (2017).

KEY

● Ammonia loading facilities ● Ammonia unloading port facilities



Current ammonia storage and transport infrastructure

There is a high level of maturity in many aspects of ammonia storage and transport infrastructure because of its widespread use as a feedstock for inorganic fertilisers. Indeed, an established worldwide ammonia infrastructure already exists with significant ammonia maritime trading. International shipping routes are well-established and there is a comprehensive network of ports worldwide that handle ammonia at large scale (Figure 5). This existing port and shipping infrastructure could enable the early accelerated adoption of large-scale transportation of ammonia as an energy vector and fuel.

The largest refrigerated ammonia storage facilities are often located at ports where ammonia is produced and then shipped internationally. As an indication of scale, the Qatar Fertiliser Company ammonia production facility has two 50,000 tonne refrigerated ammonia storage tanks which have a combined footprint of around 160m by 90m (around 1.5 hectares)[6].

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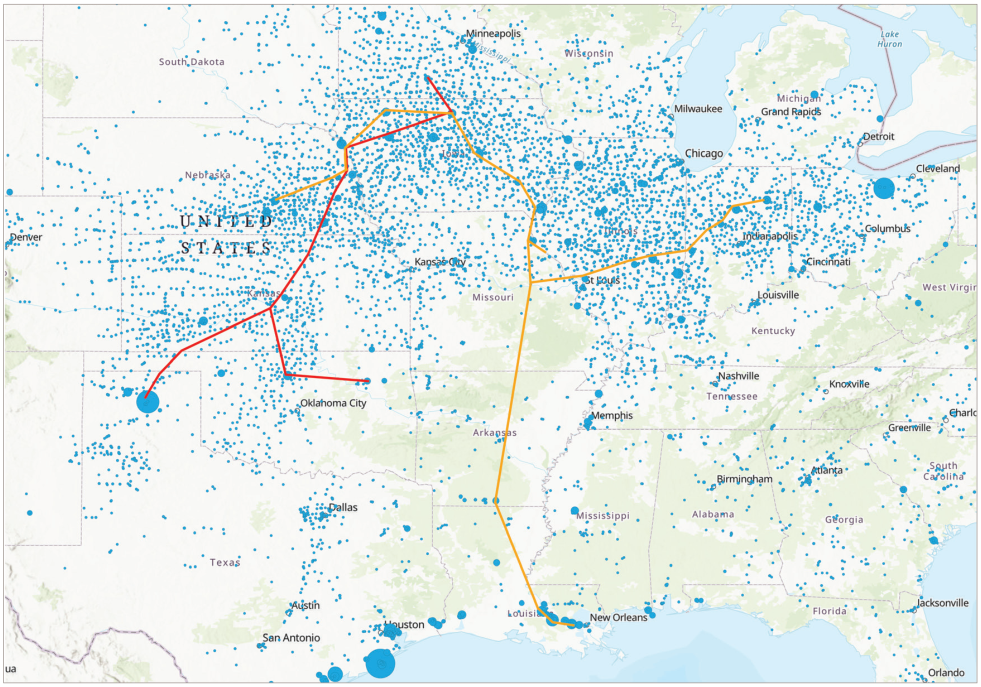
[6] McDermott. QAFCO Ammonia Storage Tanks – Snamprogetti. See www.mcdermott.com/What-We-Do/Project-Profiles/QAFCO-Ammonia-Storage-Tanks (accessed 10 June 2019).

FIGURE 6

Liquefied ammonia storage and pipeline distribution networks in the US Mid-West[7]. The Kaneb (orange line) and Magellan Midstream (red line) ammonia pipelines are respectively 2,000 miles and 1,100 miles long.



Note: The Magellan Midstream pipeline will be decommissioned in 2020.
Circle areas are indicative of ammonia tonnage. The largest circles correspond to 100,000 tonne facilities.

In the UK, ammonia is used to make nitrate fertilisers which are applied to the soil, while in the United States of America, ammonia is mainly applied directly into the soil. Consequently, the USA has over 10,000 ammonia storage sites, predominately located in the Mid-West (Figure 6); though there is a significant presence of ammonia facilities in cities such as Los Angeles (storage capacity of 150,000 tonnes in Port of Los Angeles). The highest densities are in Iowa with over 1,000 facilities and a total storage capacity of around 800,000 tonnes. Transportation is not only by road, train and river but also by pipeline; 3,000 miles of 6 – 8-inch carbon steel pipes connect 11 states with regularly spaced pumping stations, transporting around 2 million tonnes of ammonia per year[8].

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7. U.S. Environmental Protection Agency. Facility Registry Service https://www.epa.gov/frs (accessed 05 June 2019).
8. Papavinasam S. 2014 Corrosion control in the Oil and Gas Industry. Gulf Professional Publishing, 2, 41 – 131. (doi: 10.1016/B978-0-12-397022-0.00002-9).

It is essential that new applications of ammonia prevent any additional emissions.

Ammonia: health and environmental considerations

In considering expanded roles for ammonia in energy storage, the health risks from ammonia exposure and the environmental risks arising from leaks must be closely scrutinised and all systems must be designed to minimise, and effectively eliminate, these risks. Ammonia is corrosive and potentially toxic. Its high vapour pressure under standard conditions enhances the risks associated with these hazards. However, ammonia is readily detectable by smell at concentrations substantially below levels that cause any lasting health consequences.

From an environmental perspective, ammonia represents a chronic hazard to terrestrial ecosystems as well as providing an increasing burden to air pollution. Human activity has greatly modified the very important biogeochemical global cycle. The global industrial synthesis of ammonia along with combustion sources of nitrogen compounds are similar in magnitude to the natural global fixation of atmospheric nitrogen by microbes in soils and in the oceans (Figure 7).

Agricultural fertilisers account for 80% of annual ammonia production but only 17% of that nitrogen is consumed by humans in crops, dairy and meat products[9]. The remainder leaches into the soil, air and water causing widespread biodiversity losses, eutrophication, and air quality issues from particulate matter, emissions of greenhouse gases and stratospheric ozone loss[10].

Once ammonia has been applied to soils either from fertilisers or deposited from the atmosphere, it is transformed, by microbes and depending on soil conditions, to a range of other compounds including nitric oxide, nitrous oxide, and molecular nitrogen.

Although ammonia is itself not a greenhouse gas, following deposition to soil it may be converted to nitrous oxide, an important contributor to radiative forcing of climate. It also has a substantial indirect impact on climate through its role in particulate matter. One of the most significant measures to improve the resulting air pollution in the UK, and more widely in Europe, is to minimise agricultural ammonia emissions, through decreasing deposition[11]. It is therefore important and essential that any new applications of ammonia include effective measures to prevent any additional emissions. In contrast to fertilisers, nitrogen release from energy storage applications of ammonia should be as nitrogen gas only. Stringent controls, which are already present at all ammonia storage and relevant industrial sites, must be in place for ensuring that the risks of ammonia release and NO_x formation are negligible.

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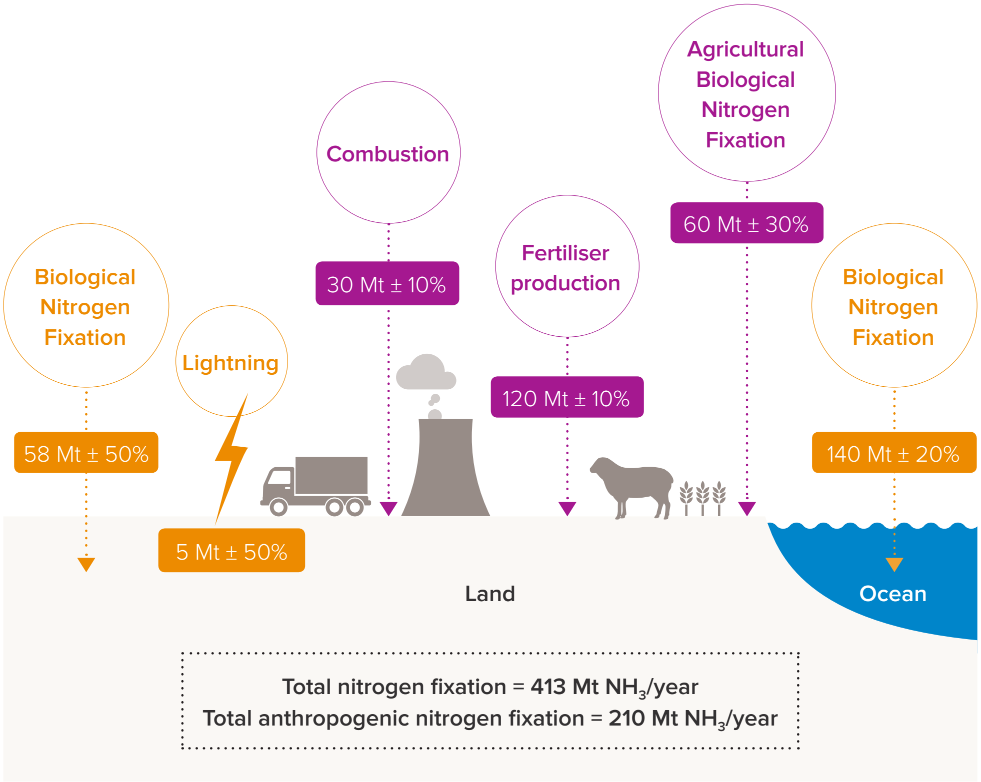
9. Leach AM *et al*. 2012 A nitrogen footprint model to help consumers understand their role in nitrogen losses to the environment. Environ. Dev. 1, 40-66. (doi: 10.1016/j.envdev.2011.12.005).
10. Erisman JW *et al*. 2013 Consequences of human modification of the global nitrogen cycle. Philosophical Transactions of The Royal Society B, 368, 20130116. (doi: 10.1098/rstb2013.0116).
11. Vieno M *et al*. 2016 The sensitivities of emissions reductions for the mitigation of UK PM2.5. Atmos. Chem.Phys.,16, 265-276. (doi:10.5194/acp-16-265-2016).

FIGURE 7

The global fixation of atmospheric nitrogen to reactive forms (ammonia, nitric oxide and nitrogen dioxide). The orange arrows represent natural processes, mainly Biological Nitrogen Fixation (BNF), the purple arrows represent anthropogenic sources[12].



Total nitrogen fixation = 413 Mt NH_3/year
Total anthropogenic nitrogen fixation = 210 Mt NH_3/year

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[12] Fowler D *et al*. 2013 The global nitrogen cycle in the twenty-first century. Philosophical Transactions of The Royal Society B, 368, 20130164. (doi: 10.1098/rstb.2013.0164).

The decarbonisation of ammonia production

Hydrogen accounts for around 90% of the carbon emissions in the synthesis of ammonia.

In this briefing the various methods of producing ammonia are differentiated using the following terms:

Brown ammonia
Higher carbon ammonia made using a fossil fuel as the feedstock

Blue ammonia
Low-carbon ammonia: brown ammonia but with carbon capture and storage technology applied to the manufacturing processes.

Green ammonia
Zero-carbon ammonia, made using sustainable electricity, water and air.

The ammonia produced is the same, it is the carbon emissions from the processes that are different

1.1 Current ammonia production process – brown ammonia

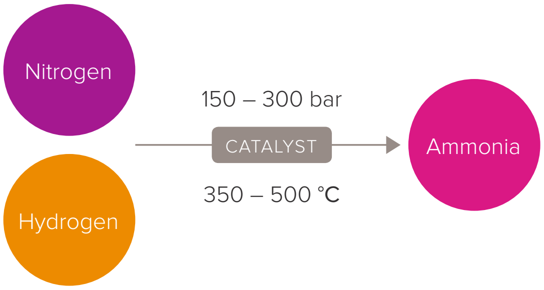
Current commercial ammonia production is predominately based around the Haber-Bosch process (Figure 8). This reaction involves the catalytic reaction of hydrogen and nitrogen at high temperature and pressure.

Overall, brown ammonia production is energy intensive, consuming 8 MWh of energy per tonne of ammonia. However, most of the energy consumption and around 90% of the carbon emissions are from the production of hydrogen.

Hydrogen is generated almost exclusively via steam reformation of fossil fuels. Most ammonia plants rely on the steam reformation of natural gas to produce hydrogen and carbon dioxide[13] (Figure 9). Coal, heavy fuel oil and naphtha can also be used but have higher carbon dioxide emissions (between 2.5 and 3.8 tonnes CO_2/tonne ammonia compared to 1.6 tonnes CO_2/tonne ammonia for natural gas[14]). The nitrogen is obtained from compressed air or an air separation unit.

FIGURE 8

Schematic of the Haber Bosch ammonia synthesis reaction.



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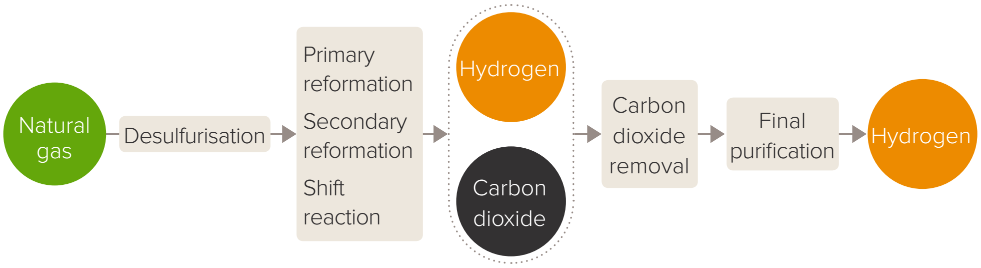
[13] International Fertiliser Industry Association. 2009 Fertilisers, Climate Change and Enhancing Agricultural Productivity Sustainably. See https://www.fertilizer.org/Public/Stewardship/Publication_Detail.aspx?SEQN=4910&PUBKEY=0E80C30A-A407-49D2-86B5-0BAC566D3B26 (accessed 29 May 2019).

[14] Brightling J. 2018 Ammonia and the Fertiliser Industry: The Development of Ammonia at Billingham. Johnson Matthey Technol. Rev., 62, 32. (doi: 10.1595/205651318x696341).

FIGURE 9

Schematic of hydrogen production via steam methane reformation.



Reducing the amount of carbon dioxide produced during the manufacturing process is dependent primarily on the source of hydrogen, using low-carbon energy for the process and system integration to produce the most efficient overall process.

The recent Royal Society Policy Briefing *Options for producing low-carbon hydrogen at scale*[15] and the Committee for Climate Change report *Hydrogen in a low-carbon economy*[16] discuss future scenarios for low-carbon hydrogen production.

Both reports note that the most likely options are:

- **Blue hydrogen**
  Steam methane reforming with carbon capture and storage (CCS).
- **Green hydrogen**
  Electrolysis of water, to generate hydrogen and oxygen in a process driven by sustainable energy.

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[15] The Royal Society. 2018 Options for producing low-carbon hydrogen at scale: Policy Briefing. See https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf (accessed 17 April 2019).

[16] Committee on Climate Change, 2018 Hydrogen in a low-carbon economy. See https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf (accessed 29 May 2019).

1.2 Blue ammonia production – using blue hydrogen from steam methane reforming (SMR) with carbon capture and storage (CCS)

While natural gas prices and carbon taxes remain low, steam methane reforming with carbon capture and storage is likely to be the lowest cost option for reducing the carbon footprint of ammonia production (CCS is estimated to add £0.40/kgH_2)[17]. Steam methane reforming emits carbon dioxide in a concentrated form that is well-suited for carbon capture and storage. However, the incorporation of carbon capture technologies into the steam methane reforming process has been modelled and shows an increase in natural gas consumption and a consequent increase in the operating cost of hydrogen production relative to the existing process[18].

While up to 90% of carbon dioxide could be captured, the upstream greenhouse gas emissions associated with natural gas extraction, limit the life-cycle emission reductions for combined steam methane reforming and carbon capture and storage to 60 – 85%[19]. This degree of carbon emission reduction is impressive but, for net-zero carbon hydrogen production, current projections suggest that this process can only be part of a transition to a zero-carbon solution. This becomes highly relevant if there is a substantial increase in hydrogen and ammonia production associated with sustainable energy storage.

1.3 Green ammonia production – using green hydrogen from water electrolysis

In this process, hydrogen is produced through the electrolysis of water, which is a well-established process (Figure 10)[20]. Nitrogen is obtained directly from air using an air separation unit which accounts for 2 – 3% of the process energy used. Ammonia is produced using the Haber-Bosch process powered by sustainable electricity.

The main challenges are cost, of which about 85% is electricity, which in most parts of the world is still significantly more expensive than natural gas. The International Energy Agency estimate that electrolysis is cost competitive with steam methane reforming with carbon capture at electricity prices between 1.5 to 5.0 USD cents/kWh (1.2 to 4.0 GBP pence/kWh); and with steam methane without carbon capture at 1 to 4 USD cents/kWh (0.8 to 3.1 GBP pence/kWh; assuming gas prices 3 to 10 USD cents/MMBtu (2.3 to 7.7 GBP pence/MMBtu))[21].

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[17] International Energy Agency. 2019 The Future of Hydrogen. See https://www.iea.org/hydrogen2019/ (accessed 29 May 2019).

[18] International Energy Agency Greenhouse Gas R&D Programme. 2017 Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS. See https://ieaghg.org/exco_docs/2017-02.pdf (accessed 23 May 2019).

[19] Committee on Climate Change, 2018 Hydrogen in a low-carbon economy. See https://www.theccc.org.uk/wp-content/uploads/2018/11/Hydrogen-in-a-low-carbon-economy.pdf (accessed 29 May 2019).

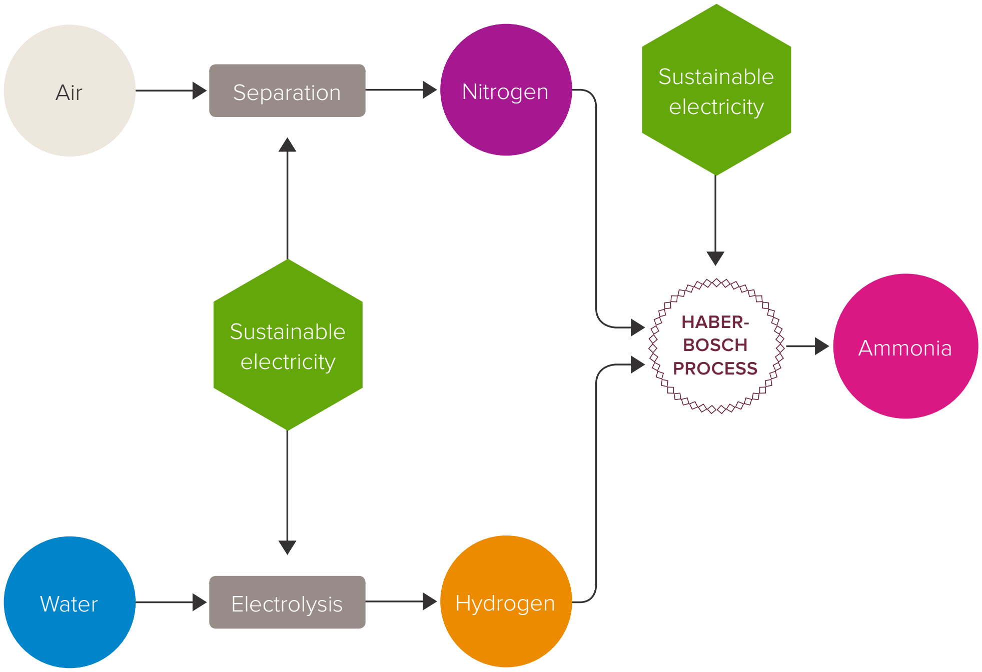
[20] The Royal Society. 2018 Options for producing low-carbon hydrogen at scale: Policy Briefing. See https://royalsociety.org/-/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf (accessed 17 April 2019).

[21] International Energy Agency. 2019 The Future of Hydrogen. See https://www.iea.org/hydrogen2019/ (accessed 29 May 2019).

The cost of electricity in areas with abundant renewable potential has decreased dramatically over the past decade. Auction prices of 4.5, 3.2 and 2.3 USD cents/kWh (3.4, 2.5 and 1.7 GBP pence/kWh) for utility-scale solar installations in Morocco, Chile and Saudi Arabia respectively, indicate that water electrolysis may already be cost competitive with steam methane reforming with carbon capture and storage in areas with optimal renewable energy conditions[22,23]. Taking advantage of such low electricity costs also requires transporting hydrogen affordably on a massive scale. Ammonia, with its existing high degree of technological readiness, is positioned to play a key role in this supply chain[24]. The production of green ammonia via electrolysis is operating at TRLs 5 – 9.

FIGURE 10

Schematic of green ammonia production based upon hydrogen production from water electrolysis and the full decarbonisation of the Haber-Bosch process.



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22. Kruger K, Eberhard A, Swartz K. 2018. Renewable Energy Auctions: A Global Overview. See http://www.gsb.uct.ac.za/files/EEG_GlobalAuctionsReport.pdf (accessed 17 April 2019).
23. International Renewable Energy Agency. 2017 Levelised costs of electricity (LCOE) 2010-2017. See www.irena.org/Statistics/View-Data-by-Topic/Costs/LCOE-2010-2017 (accessed 23 May 2019).
24. Ash N, Scarbrough T. 2019 Sailing on Solar: Could green ammonia decarbonise international shipping? Environmental Defense Fund. See https://europe.edf.org/file/399/download?token=agUEbKeQ (accessed 23 May 2019).

Figure 11 shows that the lowest current costs of green ammonia production are already competitive with blue ammonia. However, the Figure also reflects how the present costs of ammonia production vary widely across different regions due to variations in fuel and feedstock costs. This is especially evident for production via electrolysis where the cost of electricity is a major factor; the lowest electrolysis costs are from locations where renewable electricity costs are the lowest, which, globally, is solar, from areas of high global horizontal irradiance and onshore wind. In 2019, the UK strike price for future offshore wind dropped to around 4.0 GBP pence/kWh (5.2 USD cents/kWh).

1.3.1 Research opportunities

Demonstration projects for large-scale green ammonia production are likely to be electrolysis-based and sited in areas with abundant renewable electricity, such as North-Western Australia (see Chapter 3).

The development of new small-scale plant designs which couple electrolysis with ammonia production (see Case study 1) are also under development. The opportunity to combine smaller scale ammonia production with remote renewable generation is attractive, if lower capital costs can be realised. To enable ammonia to be produced at this scale, adaptation will be required to operate at a sub-megawatt scale. The downscaling of the Haber-Bosch process to small (30 – 500kW) intermittent and variable renewable energy supplies introduces two principal challenges:

- potential degradation of catalyst performance and reduction of catalyst lifetime from changes to Haber Bosch reactor temperature and pressure because of intermittent operation,
- minimisation of the inevitable efficiency loss in moving to smaller scale and non-steady state operation.

There are several recent demonstrations of ammonia production by a downscaled Haber-Bosch process integrated with water electrolysis: one such trial is in operation at the Rutherford Appleton Laboratory in Oxfordshire (see Case study 1). A similar 20kg ammonia per day demonstrator in Fukushima, Japan, which is also powered by wind, has been designed to test the cycle stability of different catalysts[25].

Energy supply intermittency may be circumvented by consuming small amounts of ammonia product to maintain constant temperature and pressure when required. Such small-scale distributed ammonia production could be used locally (eg generated on a farm and used on the land) or collected and transported by tanker to a regional energy store.

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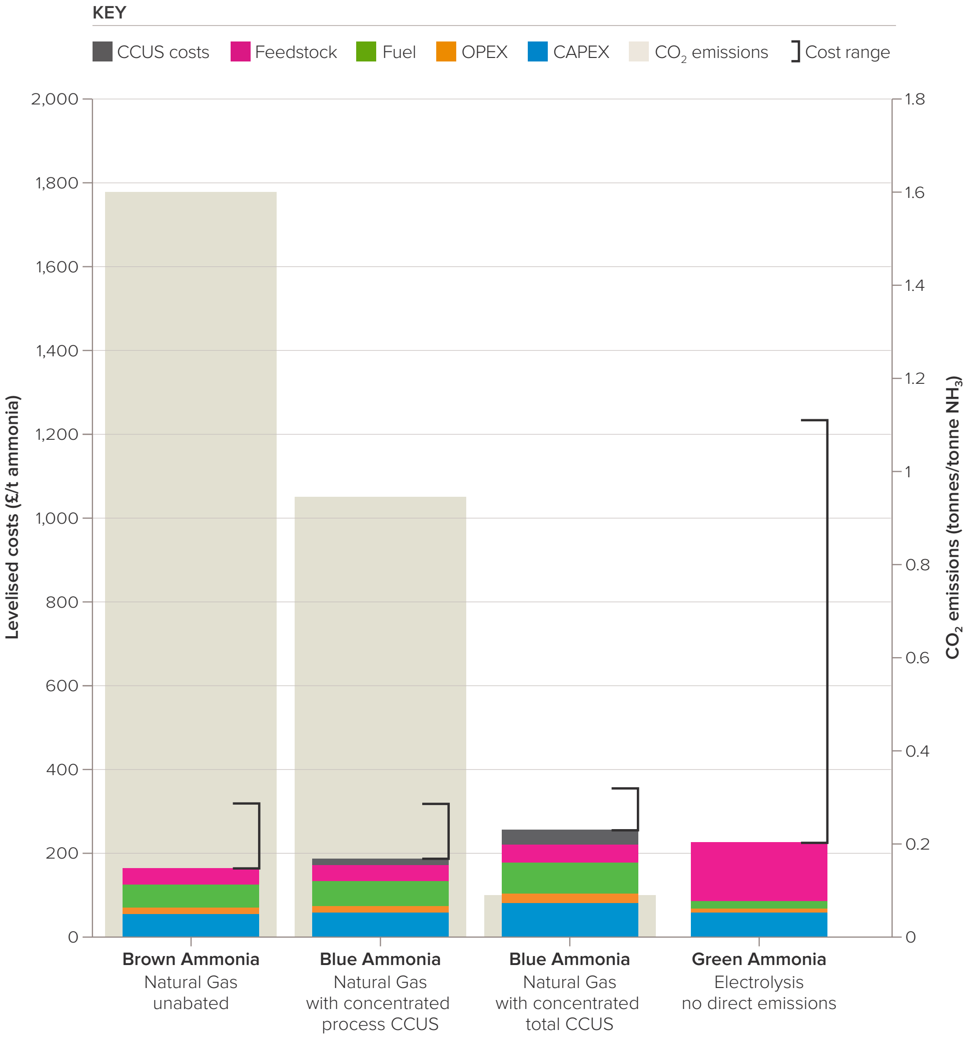
[25] Cross-ministerial Strategic Innovation Promotion Program. 2018 Press Release – World's first successful ammonia synthesis using renewable energy-based hydrogen and power generation. See www.jgc.com/en/news/assets/pdf/20181019e.pdf (accessed 10 June 2019).

FIGURE 11

Cost comparison of ammonia production via different methods[26].



Note: Range refers to the range of total levelised costs across regions, the lower end of the range is disaggregated into cost categories. Electrolysis is assumed to be powered by 100% renewable electricity; the 'feedstock cost' is the electricity for the electrolyser, and 'fuel cost' is additional electricity for the air separation unit, synthesis loop etc. CCUS costs include capture, transport and storage of carbon dioxide; process CCUS is only process emissions; total is process and energy related emissions. % carbon dioxide reduction is relative to unabated production with natural gas (1.6 tonnes/tonne NH_3).

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[26] International Energy Agency. The Future of Hydrogen, June 2019 https://webstore.iea.org/the-future-of-hydrogen (accessed Oct 2019)

Image
Green ammonia demonstration system, Rutherford Appleton Laboratory, Oxfordshire.

CASE STUDY 1

Downscaling Haber-Bosch

A team comprised of Siemens plc, Cardiff University, the University of Oxford and the Science & Technology Facilities Council (STFC), have developed a green ammonia energy demonstration system at the Rutherford Appleton Laboratory, Oxfordshire[27]. This demonstrator is designed to show feasibility and round trip efficiency through in-situ synthesis, storage and combustion of green ammonia. An on-site wind turbine generates the electricity to power both water electrolysis and the Haber-Bosch process. This system produces around 30kg/day of ammonia which is stored in a pressurised tank and a 30kW spark ignition electric generator uses this ammonia to feed electricity back into the grid.

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27. The Chemical Engineer. Green ammonia project set for launch in UK today. See https://www.thechemicalengineer.com/news/green-ammonia-project-set-for-launch-in-uk-today/ (accessed 29 May 2019).

While these demonstration projects indicate the relative technological readiness of green ammonia production, there are substantial opportunities for improvements in efficiency and cost reductions. As such, research efforts will play an important role in shaping the future of green ammonia production technologies. Some key goals include:

- Developing more active Haber Bosch catalysts will facilitate operation under milder conditions and reduce energy demand, making the process more amenable to variable and smaller-scale operation and improving its compatibility with renewable electricity. Reductions in the operating pressure to levels where expensive compressors are not required would be a valuable advance. This research and development ranges from TRLs 1 – 4.
- Ammonia separation methods: sequestering ammonia as it is produced by the use of ammonia absorption materials may facilitate lower-pressure operation and higher ammonia yields in Haber-Bosch units. Research, development and demonstration are at TRLs 1 – 5.

1.4 Novel methods for green ammonia synthesis

In addition to the Haber-Bosch process, there are other recognised methods of green ammonia production. All are still operating at a basic research stage:

1. Ammonia is produced naturally by bacteria that contain an enzyme catalyst called nitrogenase, which operates at room temperature and pressure to synthesise ammonia from water and nitrogen. Although **biological nitrogen fixation** is a perfect source of green ammonia, further research and development would be required before large-scale industrial production could be considered. This process is currently at TRL 1.
2. **Electrochemical production** is a technology for producing green ammonia directly from water and nitrogen using electricity. Importantly there is no separate hydrogen production process step. This process would be ideal for distributed (small-scale) generation and more amenable to intermittent power supplies (see Case study 2). However, to date, only low rates of ammonia production have been demonstrated in laboratory studies. New electrocatalysts, electrolytes and systems must be developed that can produce ammonia in preference to hydrogen and achieve competitive production rates[28,29]. This process is currently at TRLs 1 – 2.
3. **Chemical looping processes** involve a series of chemical/electrochemical reactions which produce ammonia as a by-product, but where the core reaction chemicals are recycled and are not lost[30,31,32]. These processes may be attractive for intermittent operation. Importantly, some of these cycles avoid the need for a separate hydrogen production process by reacting with water directly. This process is operating at TRLs 1 – 4.

There are other recognised methods of green ammonia production.

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[28] Giddey S, Badwal SPS, Kulkarni A. 2013 Review of electrochemical ammonia production technologies and materials. International Journal of Hydrogen Energy, 38, 14576–14594. (doi: 10.1016/j.ijhydene.2013.09.054).

[29] Kyriakou V *et al*. 2017 Progress in the Electrochemical Synthesis of Ammonia. Catalysis Today, 286, 2–13. (doi: 10.1016/j.cattod.2016.06.1014).

[30] McEnaney JM *et al*. 2017 Ammonia synthesis for N2 and H2O using a lithium cycling electrification strategy at atmospheric pressure. Energy & Environmental Science,10, 1621–1630 (doi: 10.1039/C7EE01126A).

[31] Gao W *et al*. 2018 Production of Ammonia via a Chemical Looping Process Based on Metal Imides as Nitrogen Carriers. Nature Energy, 3, 1067–1075 (doi: 10.1038/s41560-018-0268-z).

[32] Hargreaves JSJ. 2014 Nitrides as ammonia synthesis catalysts and as potential nitrogen transfer reagents. Applied Petrochemical Research, 4, 3–10 (doi: 10.1007/s13203-014-0049-y).

CASE STUDY 2

Process development – Solid Oxide Electrolysis Cell (SOEC)

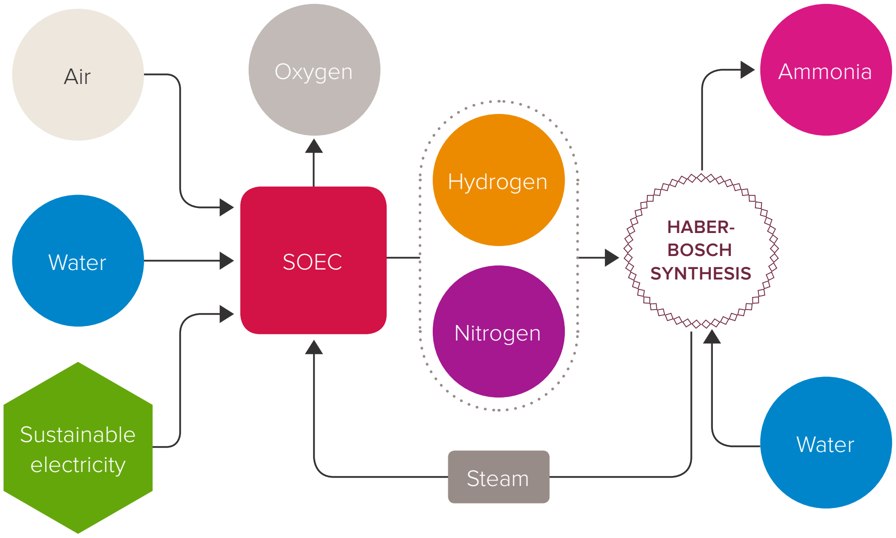
Haldor Topsoe are developing a demonstrator that integrates a solid oxide electrolysis cell (SOEC) to produce ammonia synthesis gas (H_2:N_2 = 3:1). This is then converted to ammonia via the conventional Haber-Bosch process (Figure 12). The process operates at high temperatures and can separate oxygen from air without using an air separation unit (ASU). This results in an expected energy consumption per tonne of ammonia that is 5 – 10% lower than a conventional SMR-based process and even less than a SMR-based process with carbon capture and storage.

The waste heat is used to increase the overall efficiency to over 70% of the lower heating value (LHV) of ammonia. The high overall efficiency and lower investment costs (ASUs are expensive at small scale) improve the economics of small-scale ammonia production.

Haldor Topsoe recently announced the commencement of the SOC4NH3 project (Solid Oxide Cell based production and use of ammonia), which will feature a 50kW demonstration plant using this new technology combination, with the aim of commercial availability in 2030.

FIGURE 12

Process flow diagram of ammonia synthesis using a Solid Oxide Electrolysis Cell (SOEC) to produce both hydrogen and nitrogen for the Haber Bosch process.



New zero-carbon uses for green ammonia

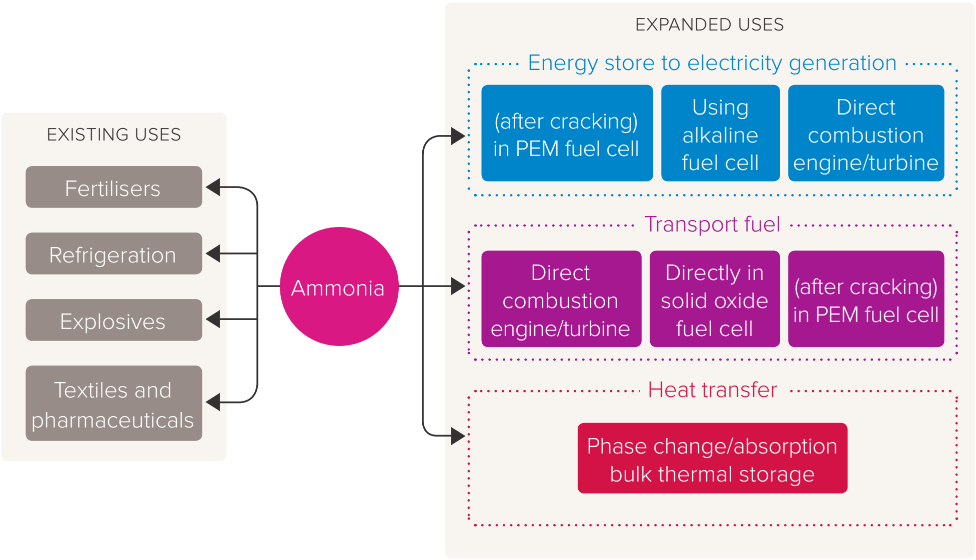
In addition to decarbonising the existing uses of ammonia, the development of green ammonia production also generates the following additional uses (Figure 13):

- Ammonia can be used as a **medium to store and transport chemical energy**, with the energy being released either directly (see Chapter 2.1) or by the full or partial decomposition of ammonia to release hydrogen (see Chapter 2.2). The hydrogen or ammonia-hydrogen mixture is then reacted with oxygen in the air to release energy.
- Ammonia can be used as a **transport fuel** by direct combustion in an engine or by chemical reaction with oxygen in a fuel cell to produce electricity to power a motor (see Chapter 2.3).
- Ammonia can also be used to **store thermal energy** through for example liquid to gas phase changes, solid to solid phase transformations and absorption with, for example, water (see Chapter 2.4).

Ammonia can be used as a medium to store and transport chemical energy.

FIGURE 13

Schematic of existing and expanded end uses of ammonia.



PEM – Proton Exchange Membrane.

2.1 The storage and transportation of sustainable energy

The energy flow in a zero-carbon economy begins with the generation of primary electricity from sustainable energy sources. Once generated, this energy must either be used immediately or stored. There are several ways of storing and recovering zero-carbon energy that include:

- electrochemical storage in batteries,
- physical storage in, for example, pumped hydroelectricity and compressed gases,
- chemical storage in the form of zero-carbon electrofuels, such as hydrogen or ammonia

Each zero-carbon storage option has its relative merits in terms of flexibility, efficiency, energy density, cost, scale and longevity. While it is always preferable to keep energy transitions to a minimum (see Chapter 2.5), additional considerations such as the energy and financial costs of storage and transport must also be considered. For example, it might be preferable to store and use hydrogen locally rather than convert it to ammonia if local, low-cost, large-scale gas storage (eg in salt caverns) is available.

Ammonia, with its relatively high energy density and existing global transportation and storage infrastructure, could offer a new, integrated worldwide sustainable energy storage and distribution solution (see, for example, Case study 3)[33]. The relative ease of storing liquid ammonia either compressed or refrigerated, particularly compared with compressed or liquefied hydrogen, makes ammonia a competitive option for storing zero-carbon energy and transporting it by pipeline, road, rail or ship (Figure 14 and Figure 15).

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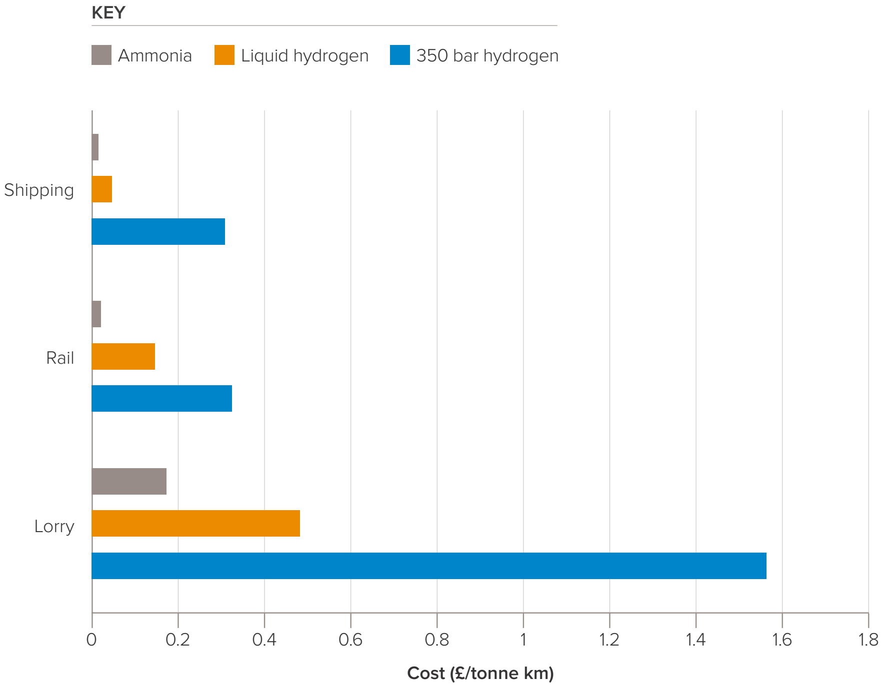
[33] Thyssenkrupp – WattshiftR. 2018 WattshiftR concept – offshore energy & ammonia production.

FIGURE 14

Estimated costs for transport of hydrogen and ammonia by lorry, rail and ship[34].



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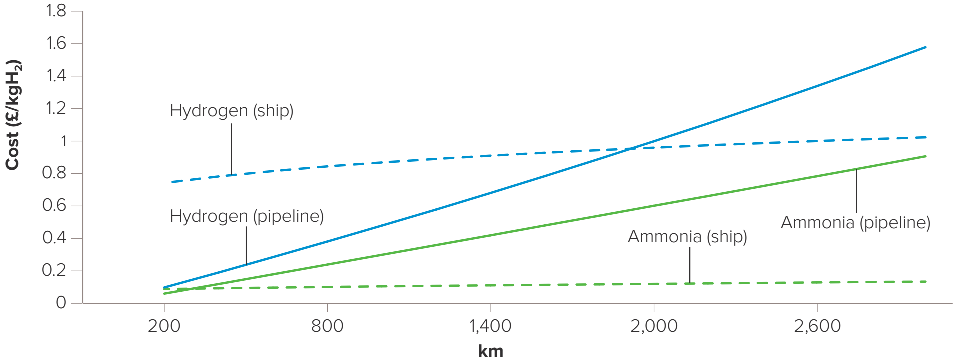
[34] ACIL Allen Consulting. 2018 Opportunities for Australia from Hydrogen Exports. See https://www.acilallen.com.au/projects/energy/opportunities-for-australia-from-hydrogen-exports (accessed 23 May 2019).

FIGURE 15

Cost estimates for transport of energy as hydrogen or ammonia by ship and pipeline[35].



Note: Hydrogen transported via pipeline is gaseous and liquefied for shipping. Costs include both the transport and storage required; not the conversion, distribution or reconversion.

Several recent studies have concluded that ammonia is the lowest-cost method and the most technologically-ready option for transporting energy over long distances (Figure 15). The cost of converting hydrogen to ammonia is around £0.80/kgH_2, so for example, the total cost of transporting ammonia 1,400km by pipeline is £1.20/kgH_2. The cost of transporting hydrogen by pipeline increases faster than ammonia, so from around 2,500km the costs are both around £1.50/kgH_2 (including the conversion cost); beyond this distance, ammonia is cheaper.

The direct use of ammonia, for example, in a direct ammonia solid oxide fuel cell or internal combustion engine, brings significant increases in both energy efficiency and reduced energy costs. There are 4,830km of ammonia pipelines in the United States and in Eastern Europe, the Tolyatti-Odessa pipeline (2400km) transports ammonia from Russia to chemical and fertiliser plants[36].

Storage cost estimates are expected to be comparable with, for example, the storage of hydrogen in salt caverns, but with the added advantages of flexibility of scale, location and onward transportation. The cost of refrigerated ammonia storage tanks varies depending upon the size, site and the facilities available, with estimates for a 10,000 tonne standalone storage tank costing between £20 – 40million.

The UK has a developed understanding of the safe handling and storage of ammonia which should permit the appropriate infrastructure to be developed.

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35. International Energy Agency. The Future of Hydrogen, June 2019 https://webstore.iea.org/the-future-of-hydrogen (accessed 24 October 2019).
36. International Energy Agency. The Future of Hydrogen, June 2019 https://webstore.iea.org/the-future-of-hydrogen (accessed 24 October 2019).

CASE STUDY 3

Storing and transporting renewable energy

The dramatic reductions in electricity costs from both onshore and offshore wind farms are advantageous for North Western Europe, and in particular for the UK. The North Sea accounts for 70% of all offshore wind capacity in Europe[37] and by 2040, offshore wind turbines in the North Sea are expected to generate 70 – 150GW of electricity; around 20% of the EU's electricity demand[38]. Utilising renewable electricity to produce ammonia will enable more flexible options for renewable energy in the energy economy.

The Energy Delta Institute and the Energy Research Centre of the Netherlands completed a feasibility study of offshore green hydrogen production on decommissioned oil/gas platforms in the North Sea linked to offshore wind farms[39]. Hydrogen would be transported onshore via existing gas pipelines (after mixing with natural gas) or by building new hydrogen pipelines. They assessed all costs associated including energy conversion, storage and transport. Using various assumptions for the output and input variables and based on market data at the time, the green hydrogen prices ranged between €1.56 – 4.67/kgH_2 (£1.33 – 3.98/kgH_2). Electrolyser capacity was also assessed for different sized platforms. Offshore array cables to connect the wind farms to the platforms cost around €465 (£396) (800m^2 array cable) to €180 (£153) (240mm^2 array cable) per metre (installation costs of €200/metre (£170/metre)). Optimal transport modes of the hydrogen between the platforms and shore were dependent on the required distance. This study involved a fresh water infeed for electrolysis, however other studies are considering sea water electrolysis[40].

ThyssenKrupp have extended this concept to explore the production of ammonia as both an energy store or hydrogen carrier[41].

To note, there are currently over 600 offshore oil and gas installations in the North Sea (470 in UK waters). A large proportion have now exceeded or are approaching end of designed lifespan and will be decommissioned in line with regulation. Recent estimates from the Oil & Gas Authority show the total cost of decommissioning remaining UK offshore oil and gas production, transportation and infrastructure are £51 billion[42].

Image
North Sea oil platform
© jgshields.

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[37] Wind Europe. 2019 Offshore Wind in Europe. See windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2018.pdf (accessed 23 May 2019).

[38] TenneT. North Sea Wind Power Hub. See www.tennet.eu/our-key-tasks/innovations/north-sea-wind-power-hub/ (accessed 23 May 2019).

[39] Jepma CJ, van Schot M. 2017 On the economics of offshore energy conversion: smart combinations. Energy Delta Institute.

[40] Meier K. 2014 Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials. International Journal of Energy and Environmental Engineering, 5, 104 (doi: 10.1007/s40095-014-0104-6).

[41] Thyssenkrupp – WattshiftR. 2018 WattshiftR concept – offshore energy & ammonia production.

[42] Oil & Gas Authority. 2019 Cost Estimate Report: UKCS Decommissioning. See https://www.ogauthority.co.uk/media/5906/decommissioning-estimate-cost-report-2019.pdf (accessed 26 November 2019).

Ammonia contains 50% more hydrogen by volume than liquid hydrogen.

2.2 Ammonia for the transportation and provision of hydrogen

The safe, effective, economical and regulated storage of hydrogen for use as a fuel in road transport is an important technological challenge in the move towards a low-carbon economy. When liquefied, ammonia contains 50% more hydrogen by volume than liquid hydrogen. These properties, along with ease of storage and transportation, make ammonia an attractive candidate for consideration for the storage and delivery of hydrogen for hydrogen fuel cell vehicles, with its high hydrogen content of 17.8wt%.

Ammonia can be straightforwardly decomposed or 'cracked' into nitrogen and hydrogen gases (Figure 16). The optimal catalytic decomposition of ammonia is critical. It can be achieved at high temperatures above 700°C using inexpensive materials such as iron. Lower temperature decomposition reduces energy costs but currently involves the use of rare-metal catalysts such as ruthenium. Further cost reductions and optimisation of catalyst and reaction processes will be required to ensure that energy losses from the ammonia decomposition reaction are close to the theoretical minimum value of about 7% of the stored energy of ammonia. Active research and innovation programmes, including in the UK, show significant promise with new inexpensive catalyst families, based on amide ($-NH_2$) and imide (-NH) materials, that operate at 450 – 500°C[43,44]. This is currently at TRLs 2 – 4.

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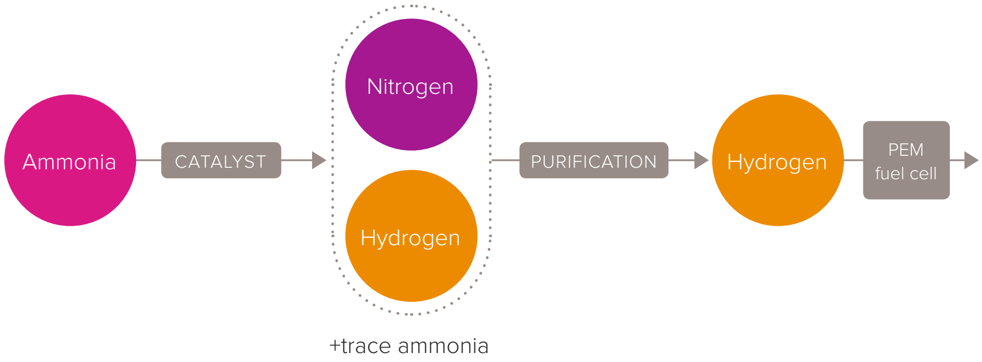
43. David WIF *et al*. 2014 Hydrogen Production from Ammonia Using Sodium Amide. J Am Chem Soc,136, 13082–13085. (doi:10.1021/ja5042836).
44. Makepeace JW, Wood TJ, Hunter HMA, Jones MO, David WIF. 2015 Ammonia decomposition catalysis using non-stoichiometric lithium imide. Chem Sci, 6, 3805–3815. (doi:10.1039/C5SC00205B).

FIGURE 16

Cracking ammonia to hydrogen to be used in a Proton Exchange Membrane (PEM) Fuel Cell.



Its high hydrogen content and established storage and transportation options make ammonia an attractive source of hydrogen. The hydrogen generated from the decomposition of ammonia can be used to generate electricity, typically today using proton exchange membrane (PEM) fuel cells. PEM fuel cells can be used to power vehicles and also for static isolated and grid electricity generation.

They are, however, sensitive to very low levels (<1ppm) of ammonia in the hydrogen gas stream; for both environmental and process reasons, the ammonia limits must be kept below 1ppm. Post-cracking purification is therefore a critical technical step for obtaining a usable hydrogen stream. Several approaches are being developed to purify the hydrogen stream produced from ammonia decomposition before its use in a PEM fuel cell, including membranes[45] and absorption-based systems[46].

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45. Lamb KE *et al*. 2018 High-Purity H2 Produced from NH3 via a Ruthenium-Based Decomposition Catalyst and Vanadium-Based Membrane. Ind. Eng. Chem. Res, 57, 8–13. (doi: 10.1021/acs.iecr.8b01476).
46. van Hassel BA *et al*. 2015 Ammonia sorbent development for on-board H2 purification. Separation and Purification Technology, 142, 215-226. (doi: 10.1016/j.seppur.2014.12.009).

Ammonia can be burned in internal combustion engines.

2.3 Technological opportunities for ammonia as a transport fuel

There are several power technologies that work well with ammonia (or ammonia-derived hydrogen) as an energy source. Ammonia can be reacted with oxygen from the air in a fuel cell to produce electricity or it can be burned in internal combustion engines and gas turbines. All uses have their advantages, challenges and requirements for research and development (see Table 1).

TABLE 1

Fuel technologies applicable to ammonia.

Technology (efficiency)	Required pre-treatment	Capital Cost (£/kW)
Proton exchange membrane (PEM) fuel cell (40 – 50%)	Ammonia decomposition Trace ammonia removal	100 (mobile)
		1,300 (stationary)
Alkaline fuel cell (AFC) (50 – 60%)	None	1300 (stationary)*
Solid oxide fuel cell (SOFC) (50 – 65%)	None	760 (stationary)
Internal combustion engine (ICE) (30 – 40%)	Ammonia can be used directly but partial decomposition is beneficial	30 – 45 (mobile)
		1,000 (stationary)
Boilers and Furnaces (85 – 90%)	None	150 – 350 (stationary)
Combined cycle gas turbine (CCGT) (55 – 60%)	Ammonia can be used directly but partial decomposition is beneficial	750 (stationary)

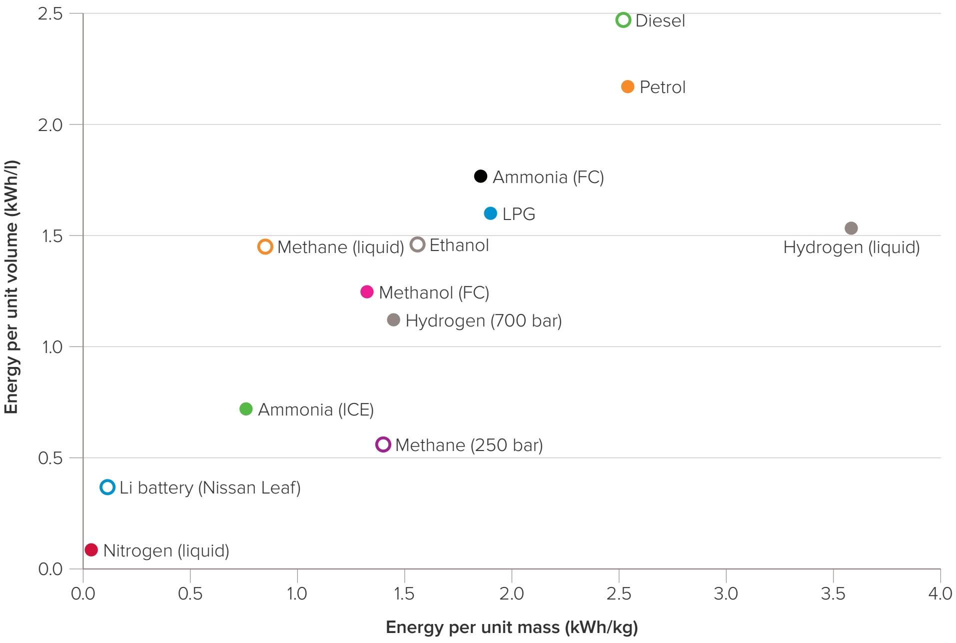
Estimated cost values for mobile and static applications are based on current technologies that are under development.

*Currently, there are no AFCs that would be close to technological readiness for a mobile system. For stationary systems, from a raw materials viewpoint, it would be expected that the price would be competitive with other fuel cell systems, but only two companies are currently developing them, so data is not available on these systems.

Advantages	Challenges	R&D Focus
Established technology Suitable for mobile applications	Cost and use of platinum Sensitive to un-cracked ammonia	Trend for decreasing platinum use Development of ammonia technologies
Non-use of platinum (or similar metals) Highly tolerant of ammonia	Low energy density Few commercial suppliers Requires carbon dioxide scrubbing	Increase in energy density Improve suitability for stationary applications Innovation for carbon dioxide scrubbing Direct ammonia systems
Established technology Decomposes ammonia in-situ Non-use of platinum (or similar metals)	High temperatures of operation Large-scale commercialisation Corrosion of components	Improve suitability for stationary applications, combining heat and power Investigate for transportation applications Reduction of oxidation impacts
Established technology with other fuels (ie ammonia mixtures with gasoline, diesel, hydrogen, etc.) Robust technology High power density	Pure ammonia combustion still under development NO_x gases and ammonia slip need to be limited Low efficiency	Development of novel ammonia cracking systems Ammonia can be used to remove NO_x gases Improved combustion technologies to fully burn ammonia
Established technology at low ammonia content (up to 20 wt%) Very robust technology High power outputs (>1MW)	Increase in ammonia content Reduction of ammonia slip NO_x gases need to be limited Corrosion caused by aggressive atmospheres	Improvement in injection and combustion technologies Development of new systems that use new materials and innovative distribution concepts
High power outputs (>1MW) Support to produce power during peak consumption times Full cycle development (heat, power, cooling)	Ammonia complete combustion still under development NO_x gases need to be limited Technology under development: NO_x gases are required to be limited	Development of new combustors for efficient burning Ammonia can be used to remove NO_x gases during combustion Global (Japan) efforts to design a large power unit by 2030

FIGURE 17

Specific energy and energy density of a range of energy stores for mobile applications accounting for typical container properties and energy conversion technology efficiencies.



ICE – Internal combustion engine, FC – fuel cell, LPG – liquid propane gas.

Figure 17 shows a comparison of various fuels (including storage weights and efficiencies) for mobile applications using a range of different energy sources. Although hydrocarbon fuels store more energy, the greater efficiency of ammonia powered fuel cells means that, for example, direct ammonia fuel cells have a similar overall performance to liquid propane gas (LPG) powered internal combustion engines. Potential alternative low-carbon energy vectors, such as lithium batteries and liquid-to-gas expansion systems, have a much lower energy density than all chemical storage options and their suitability is dependent on the energy demands of the journey.

Ammonia is a suitable fuel for transport modes where large amounts of energy are required for extended periods of time and where batteries or direct electrical connection are not practical or cost effective. Examples include heavy good vehicles, trains, aviation and shipping (see Case study 4). The MAN Energy Solutions' demonstration programme to retrofit current liquid natural gas marine engines to run on ammonia, offers an economically feasible route toward the decarbonisation of large-scale maritime transportation. Progress in the modification of internal combustion engines and gas turbines to run on ammonia similarly offers a viable transition that is based around retrofitting current technologies which impact both transportation and electricity production. Combustion of ammonia may also help meet industry requirements for process heat in areas which are difficult to electrify, fulfilling a role which is currently played by fossil fuels. Similarly, ammonia could also be used to provide green hydrogen for low-carbon steelmaking methods[47].

Direct ammonia solid-oxide fuel cells offer a high efficiency route both for transportation and future electricity production. Advances in solid oxide fuel cells, for example from the NASA Glenn Research Center[48], have led to high specific and volumetric power densities of up to 2.5kW/kg and 7.5kW/l that are sufficient to power unmanned aerial vehicles and have the potential to facilitate the reduction of carbon emissions from aviation.

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[47] International Energy Agency. 2017 Renewable Energy for Industry. See https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf (accessed 24 October 2019).

[48] NASA Technology Transfer Program. 2017 High Power Density Solid Oxide Fuel Cell. See https://ntts-prod.s3.amazonaws.com/t2p/prod/t2media/tops/pdf/LEW-TOPS-120.pdf (accessed 10 October 2019).

2.4 The use of ammonia in heating and cooling

In addition to using ammonia combustion as a source of heat, ammonia can also store and release significant energy on changing between its liquid and gas forms (1371.2 kJ/kg at atmospheric pressure). It has the potential to become significant in the decarbonisation of space heating and cooling. Star Refrigeration, based in the UK, has recently developed and installed heat pumps based on ammonia, that can use low-grade waste heat to generate heated water up to 90°C.

Ammonia can also be used in thermochemical heat storage systems, where the reversible reaction of ammonia and a metal salt can be used to store and release heat. These systems are at a proof-of-concept stage and could find practical application in long-term heat storage for buildings.

2.5 Energy conversion efficiency

The process of converting water and air into ammonia using electrolysis and the Haber-Bosch process consumes energy. Similarly, the cracking of ammonia to hydrogen also consumes energy, as does the conversion of hydrogen to electricity in a fuel cell. It is possible to calculate all these losses and express them as a percentage overall efficiency – a measure of the energy output compared to the energy input. In general, the greater the number of processes involved, the lower the overall efficiency, although this depends upon the efficiency of those processes. Overall efficiencies for different ammonia uses are shown in Table 2, along with hydrogen for comparison. The efficiency of application becomes the main consideration, if cheap green ammonia becomes an internationally traded energy commodity.

TABLE 2

Modelled efficiencies for energy provided from primary electricity[49].

Process	Efficiency of ammonia or hydrogen production (renewable power from wind & solar)	Efficiency of application	Overall efficiency
Ammonia from electrolysis and Haber-Bosch, used with a **solid oxide fuel cell** to produce electricity	55 to 60%	50 to 65%	28 to 39%
Ammonia from electrolysis and Haber-Bosch burned in an **internal combustion engine**	55 to 60%	30 to 40%	17 to 24%
Hydrogen cracked from ammonia obtained by electrolysis and Haber-Bosch, and used in a **PEM fuel cell**	40 to 50%	40 to 50%	15 to 25%
Hydrogen from electrolysis and used in a **PEM fuel cell**	65 to 70%	40 to 50%	26 to 35%

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[49] Giddey S, Badwal SPS, Munnings C, Dolan M. 2017 Ammonia as a Renewable Energy Transport Media. ACS Sustainable Chem Eng., 5, 10231-10239. (doi:10.1021/acssuschemeng.7b02219).

CASE STUDY 4

Decarbonising the international maritime sector

The International Maritime Organisation has committed to reducing greenhouse gas (GHG) emissions from international shipping by at least 50% (compared to 2008) by 2050. One of the key challenges in achieving these targets is the long lifetime of large ships (around 25 years).

The maritime industry has already identified the significant retrofitting potential for ammonia as a green fuel for shipping, noting its ease of storage, existing maritime networks and bunkering capabilities, flexible use in both combustion engines and fuel cells and potential relative to other decarbonisation options[50].

A recent Environmental Defence Fund (EDF) report discusses the decarbonising potential of ammonia in the international maritime sector and highlights Morocco, which is already investing in large-scale solar energy generation, as a potential key player with large commercial ports close to key shipping routes and an abundance of renewable energy resources[51]. These include a total potential for offshore wind of around 250GW, which is approximately 25 times the current generating capacity in the country and would provide 770TWh of electricity annually, which is sufficient to produce green ammonia for about a third of the international shipping fleet.

MAN Energy Solutions, a designer and manufacturer of marine engines, have committed to decarbonising the maritime economy starting with fuel decarbonisation in container shipping. They are currently developing ammonia fuelled-engines based on current liquid natural gas technology and anticipate that the first ammonia engine could be in operation by early 2022[52]. MAN Energy Solutions is also in the process of obtaining flag state approval to use ammonia as a marine fuel in the IGC Code (International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk). The accredited classification society, DNV-GL, with 24% of the market share in shipping, are also pursuing the use of ammonia as a marine fuel. Other developments include Lloyd's Register granting Approval in Principle to SDARI (Shanghai Merchant Ship Design & Research Institute) for the design of a 180,000 ton ammonia-fuelled bulk carrier[53] and announcing a project for an ammonia-fuelled 23,000 TEU ultra-large container ship (ULCS) concept design from MAN-ES and DSIC (Dalian Shipbuilding Industry Co)[54]. Furthermore ABS (American Bureau of Shipping), MAN-ES and SDARI are collaborating to develop ammonia-fuelled feeder vessels[55].

TEU – Twenty-foot equivalent units.

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[50] Gong W, Willi ML. 2008 United States Patent Application Publication – Caterpillar Inc. See https://patentimages.storage.googleapis.com/b4/b0/74/315157b86c9292/US20100019506A1.pdf (accessed 14 November 2019).

[51] Ash N, Scarbrough T. 2019 Sailing on Solar: Could green ammonia decarbonise international shipping? Environmental Defense Fund. See https://europe.edf.org/file/399/download?token=agUEbKeQ (accessed 23 May 2019).

[52] MAN Energy Solutions. 2019 Engineering the future two-stroke green-ammonia engine. See https://marine.man-es.com/docs/librariesprovider6/test/engineering-the-future-two-stroke-green-ammonia-engine.pdf?sfvrsn=7f4dca2_4 (accessed 14 November 2019).

[53] Shanghai Merchant Ship Design & Research Institute. 2019 Linkedin https://www.linkedin.com/posts/shanghai-merchant-ship-design-%26-research-institute_180k-dwt-bc-of-carbon-free-issued-and-obtained-activity-6609776461731717120-oZtk/ (accessed 20th December 2019).

[54] Lloyd's Register. 2019 Industry project to design ammonia-fuelled 23k ULCS concept. See https://www.lr.org/en/latest-news/aip-ammonia-fuelled-ulcs/ (accessed 20 December 2019).

[55] American Bureau of Shipping (ABS). 2019 ABS, MAN & SDARI join forces to develop ammonia-fuelled feeder vessel. See https://ww2.eagle.org/en/news/press-room/abs-man-sdari-develop-ammonia-fueled-feeder-vessel.html (accessed 20 December 2019).

International perspectives: activities and future opportunities

There is significant future export potential for stored renewable energy[56]. Indeed, the ability to store and transport sustainable energy worldwide may be one of the cornerstones of a zero-carbon energy future. First plans for the international trading of ammonia as a renewable energy commodity involve rich, solar- and wind-resourced countries and regions. The UK has an excellent source of renewable wind energy and has the technological know-how to be a world leader in the development and use of green ammonia. Developments in three other countries are highlighted here to demonstrate the global effort in green ammonia.

3.1 Japan

In 2015, the Japanese government launched the R&D programme *Strategic Innovation Promotion Program – Energy Carriers*, which focused on the entire hydrogen energy value chain, from production, through transportation and storage, to consumption. These technologies will be demonstrated at the Tokyo Olympics in 2020. Part of the programme explored the potential routes for importing significant quantities of hydrogen-containing materials produced in locations with abundant renewable energy potential such as Australia and the Middle East. The energy storage methods under investigation were liquid hydrogen, liquid organic hydrides (with primary focus on methyl cyclohexane) and ammonia . As a result of the Energy Carriers demonstrations, the Ministry of Energy, Trade, and Industry added ammonia to its latest technology roadmap. This has been signed into law and the new Hydrogen Basic Strategy has called for imports of carbon-free ammonia "by the mid-2020s"[57].

Low levels of ammonia in co-firing with coal and natural gas have demonstrated stable combustion in Poland and Japan, while companies such as IHI (Japan) have announced initial trials to supply power up to 2MW in one of their coal-converted units, with a goal to replace more than 20% of coal for the production of cleaner power[58]. Similarly, the chemical company, Ube Industries Ltd. has successfully replaced coal with ammonia in initial tests for clinker production, and have found that the quality and strength of the final product remained the same.

Research is also underway which demonstrates the feasibility of ammonia:hydrogen blends for burning in gas turbines[59]. This indicates ammonia has the potential for use in combined cycle gas turbines (CCGT), which provide a high degree of flexibility in meeting electricity demand and compensating for the variability in renewable electricity from wind and solar sources.

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[56] Cross-ministerial Strategic Innovation Promotion Program (SIP). 2015 Energy Carriers. See http://www.jst.go.jp/sip/pdf/SIP_energycarriers2015_en.pdf (accessed 14 October 2019).

[57] Ministerial Council on Renewable Energy Hydrogen and Related Issues. 2017 Basic Hydrogen Strategy. See https://www.meti.go.jp/english/press/2017/pdf/1226_003b.pdf (accessed 14 October 2019).

[58] IHI Corporation. 2018 World's highest level of combustion test facilities for coal-fired power plants. See https://www.ihi.co.jp/ihi/all_news/2017/technology/2018-3-28/index.html (accessed 14 October 2019).

[59] Kobayashi H, Hayakawa A, Somarathne KDKA, Okafor EC. 2019 Science and technology of ammonia combustion. Proceedings of the Combustion Institute, 37, 109-133. (doi: 10.1016/j.proci.2018.09.029).

3.2 Australia

Given its significant potential for large-scale, low-cost renewable electricity, Australian federal and state governments and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) have recently published several hydrogen roadmap documents, which lay out a trajectory to large-scale production and export of hydrogen from Australia. These plans include the synthesis of green ammonia[60]. In total, the Australian Renewable Energy Agency (ARENA) has granted A$2.9million (approx. £1.5million) to deliver feasibility studies at two ammonia plants in Queensland. Firstly, A$1.9million (approx. £1million) worth of federal grants was provided to Queensland Nitrates Pty Ltd (QNP) to fund a technical and economic feasibility study that will assess the production of renewable ammonia at a commercial scale using an existing plant in Central Queensland. The aim is to produce 20,000 tonnes of ammonia per year (around 20% of Queensland's nitrate demand)[61]. The second plant is in Moranbah, Queensland, where around A$1million (approx. £520,000) was awarded to Dyno Nobel to conduct a similar feasibility study. Both studies aim to identify methods to accelerate the development of industrial-scale electrolysis equipment and help lower the costs.

In Western Australia, another recent example is the feasibility study by ENGIE SA and YARA International ASA to design a green hydrogen plant that would be integrated with an existing YARA ammonia plant in Pilbara[62].

CSIRO has been developing membrane technology to produce pure hydrogen streams from cracked ammonia suitable for refuelling PEM fuel cell vehicles[63]. This technology was demonstrated in 2018 and is currently in commercial development.

3.3 China

Recent International Energy Agency analyses have explored the potential to significantly reduce the cost of renewably-produced hydrogen and ammonia by using a combination of wind and solar resources in areas of East China[64]. The analysis showed that by using these renewable energy resources, cost reductions in the region of 10 – 20% could be achieved, particularly if the Haber-Bosch process could be run with increased flexibility than current modes of operation. If realised, the estimated lowest cost of ammonia values of between £380 – 420/tonne are close to being competitive with coal-based ammonia production in the region even without CCS costs added.

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60. Bruce S *et al*. 2018 National Hydrogen Roadmap. CSIRO, Australia.
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Conclusion

The global production of 176 million tonnes of ammonia per year accounts for around 1.8% of overall global carbon dioxide emissions. To meet net-zero targets, an urgent plan to decarbonise ammonia production must be developed and implemented, which in turn would open opportunities for ammonia to replace fossil fuels in other applications.

The majority of the carbon dioxide emitted during ammonia production comes from the steam methane reforming (SMR) process for hydrogen production. In the short-term, to manage the transition to net-zero carbon systems, 'blue hydrogen' can be produced by incorporating carbon capture and storage alongside the SMR process. This is unlikely to be a long-term solution in a zero-carbon economy.

The electrolysis of water to produce 'green hydrogen' offers a pathway to zero-carbon ammonia production but relies on low-cost sustainable electricity and continuing reductions in electrolyser costs. Renewable energy electricity costs from regions rich in wind and solar energy (at prices between 1.7 and 3.4 GBP pence/kWh) are already close to a tipping point for the affordable production of zero-carbon green ammonia. The value of a green ammonia market would significantly strengthen the economic opportunities to extend renewable penetration into the energy economy. However, while the overall efficiency remains poor, the energy system must be considered to ensure that production of ammonia is relevant to the local situation.

There are several processes that could be developed with further research to produce 'green ammonia' that include new production catalysts, electrochemical ammonia production and chemical looping processes. Some of these technologies may address the challenges of directly coupling ammonia production to intermittent renewable power.

In addition to decarbonising the existing uses of ammonia, such as the production of fertilisers for agriculture, the production of green ammonia from green hydrogen could offer further options in the drive to reduce greenhouse gas emissions:

- As an **energy storage medium**, ammonia is easily stored in large quantities as a liquid at modest pressures (10 – 15 bar) or refrigerated to -33°C. In this form, its energy density is around 40% that of petroleum.
- As a **zero-carbon fuel**, can also be used in fuel cells or by combustion in internal combustion engines, industrial burners and gas turbines. The maritime industry is likely to be an early adopter of ammonia as a fuel. Ammonia also has the potential to be used to decarbonise rail, heavy road transport and aviation.
- To **generate electricity** through fuel cells, gas turbines or international combustion engines to provide power to the grid or remote locations.
- As an **effective energy carrier** for nascent international sustainable energy supply chains. It is lower cost and significantly easier to store and transport than pure hydrogen, has existing international infrastructure, can be cracked to produce hydrogen when required and is itself a zero-carbon fuel.
- Has the potential to be used in **district heating** systems.

A global manufacturing and distribution system is in place. While the safe transportation and use of ammonia is well-established, new applications will require careful risk assessment and additional control measures may be required to reduce risks to health and the environment.

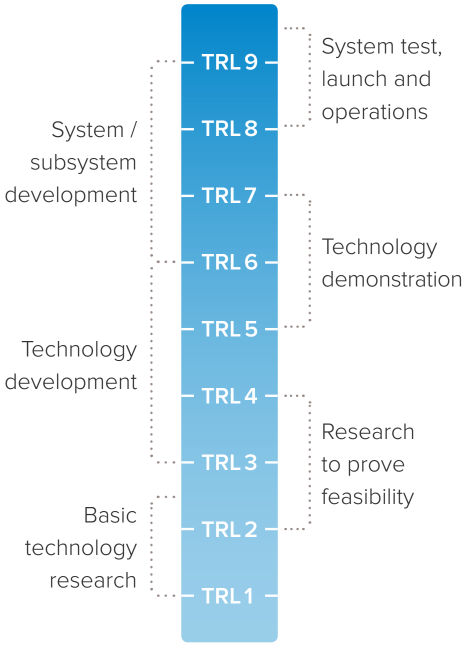
The UK possesses expertise in catalysis, combustion, fuel-cell technologies and electrolysis that will be key to improving the efficiencies and reducing the costs of ammonia combustion, low-carbon hydrogen production, ammonia cracking and the development of a broad range of fuel cell technologies.

Annex A: Definitions

Technology readiness levels (TRL)

Technology Readiness Levels (TRLs) are a technology management tool that provides a measurement to assess the maturity of evolving technology.

System	Technology readiness level (TRL)
Hydrogen production from ammonia	
Ammonia cracking (>700°C)	7 – 9
Ammonia cracking (~450°C) (non-precious metal)	2 – 4
Ammonia purification	3 – 6
Ammonia production methods	
Decarbonised Haber Bosch	5 – 9
Chemical looping processes	1 – 4
Electrochemical production	1 – 3
Biological 'nitrogen fixation' production	1
R&D: decarbonised Haber Bosch production	
Improving Haber Bosch catalysts (lower temperature)	1 – 4
Ammonia separation methods (lower-pressure operation)	1 – 5



Units used in the report.

In the International System of units (SI), energy is measured in joules (J). Power is the rate of energy used and is measured in joules per second or watts (W).

The SI system uses the following scale prefixes:

Number	Name	Symbol
1,000	Kilo	k
1,000,000	Mega	M
1,000,000,000	Giga	G
1,000,000,000,000	Tera	T
1,000,000,000,000,000	Peta	P

To simplify the numbers (eg for domestic energy bills), energy is sometimes quoted in watt hours (Wh), which is the amount of energy used at a rate of one watt for one hour = 3,600 Joules.

For example: running a 1,000 watt (1 kW) heater for 1 hour has used 1,000 Wh or 1 kWh of energy (if expressed in joules this would be 3,600,000 J or 3.6 MJ)

Energy content is often expressed in multiples of watt hours eg MWh, GWh, TWh.

Rate of production given in multiples of watts eg MW, GW.

Btu = The British thermal unit is a non-SI, traditional unit of heat. MMBtu is 1,000,000Btu and is equivalent to 293kWh.

Currency exchange (as of 28 November 2019)

1USD	0.774GBP
1EUR	0.852GBP
1AUD	0.524GBP

Annex B: Acknowledgements

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