

Ammonia

New possibilities for hydrogen storage and transportation



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Executive summary

The idea of using ammonia (NH₃) as a hydrogen carrier or direct gasoline replacement has been discussed for over 70 years. However, with concerns regarding global warming intensifying, and few signs of a practical hydrogen solution on the horizon, it seems appropriate to revisit this carbon-free substance as a possible alternative fuel.

The findings of this report may be summarised as follows:

- Ammonia has many physical properties that endow its candidature as hydrogen carrier and fuel. Containing more hydrogen than pressurized or liquefied hydrogen itself, it is easily stored in comparatively inexpensive and low-pressure containers.
- Ammonia is unique as a fuel since it neither contains carbon nor necessarily emits carbon during its production. Using renewable hydrogen feedstocks, or purely biological methods, environmentally friendly ammonia can be manufactured using a succession of carbon-free routes that can be developed and adopted in accordance with evolving market demands and economics. Existing ammonia manufacturing techniques, namely methane reforming, can be modified to cut CO₂ emissions by 77% compared to gasoline on a World-to-wheel™ basis. Ultimately, however, ammonia produced from renewable hydrogen, or directly via biological processes such as anaerobic digestion or bacterial nitrogen fixation, would eliminate carbon dioxide emissions altogether.
- Ammonia is the second most widely used chemical in the world and is distributed via an international network of pipelines, railroads, barges, ships, road trailers, and storage depots. Although designed to serve the needs of the fertilizer and chemical industries, this infrastructure illustrates the feasibility of safely and efficiently transporting huge quantities of ammonia from remote production sites to local markets.
- Ammonia is toxic at concentrations 100 times higher than detectable by most people. However, whilst it might be argued that *accidental* releases of ammonia present a greater toxicity hazard than comparable quantities of gasoline or diesel, the same can not be said about the *unavoidable* exhaust products of each: ammonia burns in air to produce inert nitrogen and water, while diesels exhausts contain over 40 air contaminants recognised as toxicants, carcinogens, reproductive and developmental hazards, and endocrine disrupters. Furthermore, ammonia is virtually non-flammable, a property that should reduce the frequency of deaths and injuries caused by vehicle fires.
- Ammonia can be converted into useful energy either directly, i.e. in a spark ignition engine or electrochemical fuel cell, or indirectly via its dissociation into hydrogen. The former is facilitated using a catalyst gas such as hydrogen. Alternatively, ammonia can efficiently be dissociated into hydrogen and nitrogen using electrolysis or thermocatalytic decomposition. To be viable as a source of hydrogen fuel cell vehicles, however, the catalyst loading and operating temperature of electrolyzers and thermal crackers respectively must be reduced.

In conclusion, subject to technological improvements, this study finds ammonia may have a useful role to play in the realisation of a global hydrogen economy. The challenges ahead are formidable, not least the development of appropriate standards governing the storage and transportation of ammonia, however these and related concerns seem minor compared to the resultant environmental and societal benefits.

This report was commissioned by ACTA SpA, an Italian catalyst producer.

Introduction

Even by the most generous estimates the world is facing an uncomfortable future. Regardless of whether crude oil reserves have peaked or not, unstoppable global economic expansion seems certain to aggravate global warming via increased carbon dioxide emissions. Well intentioned attempts to arrest the ensuing environmental disaster by converting society to a carbon-free world, the fabled “hydrogen economy”, have been frustrated by the inability to satisfactorily store or transport this elemental gas.

Yet this is not the first time humankind has been confronted by an apocalyptic energy crisis. In the late 19th century it was acknowledged that existing sources of nitrogen fertilizer, primarily Chilean saltpetre, could not sustain prevailing rates of corn production in Europe and North America. Using phrases eerily familiar to modern environmentalists, Sir William Crookes described his Malthusian nightmare in an address to the British Association in 1898:

“The fixation of atmospheric nitrogen is one of the greatest discoveries awaiting the ingenuity of chemists. It is certainly deeply important in its practical bearing on the future welfare and happiness of the civilised races of mankind.... The fixation of nitrogen is vital to the progress of civilised humanity. It is a question of the not far-distant future.”

Within 20 years a German chemist named Fritz Haber had provided the answer: anhydrous ammonia (NH_3) produced via a high-pressure catalytic process. In essence, atmospheric nitrogen was “fixed” by bonding it chemically with hydrogen obtained from natural gas. This provided a synthetic fertilizer that supplemented the ammonia produced naturally during the nitrogen cycle.

Industrialised by Haber and Bosch in the 1920’s, the fixation of atmospheric nitrogen remains the single-most important chemical reaction in the world today. It is estimated some 40% of the world’s population owe their survival to food fertilized by nitrogen delivered by synthetically prepared ammonia.

This White Paper discusses how ammonia — not for the first time — may provide a solution to a global energy crisis: the safe and efficient transportation of hydrogen. Instead of using ammonia to fix and convey atmospheric nitrogen, renewably produced hydrogen can be transported in the form of NH_3 . Alternatively, ammonia can be burnt directly in a modified spark ignition engine. Since it contains no carbon this would result in zero tailpipe emissions.

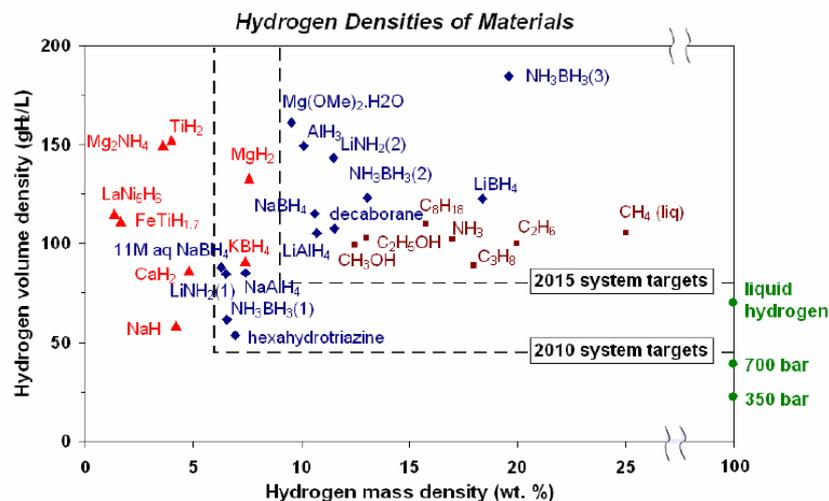
Physical properties

Ammonia has many physical properties that endow its candidature as a hydrogen carrier or direct gasoline replacement. Easily liquefied under modest pressure, ammonia can be stored for long periods in inexpensive and lightweight containers. Containing 17% hydrogen by weight, the mass density of ammonia exceeds U.S. Department of Transportation system targets for 2010 (6 wt.%) and 2015 (9 wt.%). On a volumetric basis, ammonia contains more H₂ than pressurized or liquefied hydrogen itself.

Hydrogen density

The U.S. Department of Energy has set targets for the hydrogen volume density and hydrogen mass density of transportation fuels. As illustrated in Figure 1, anhydrous ammonia (NH₃) exceeds both the 2010 and 2015 targets.

Figure 1: U.S. Department of Energy hydrogen storage targets

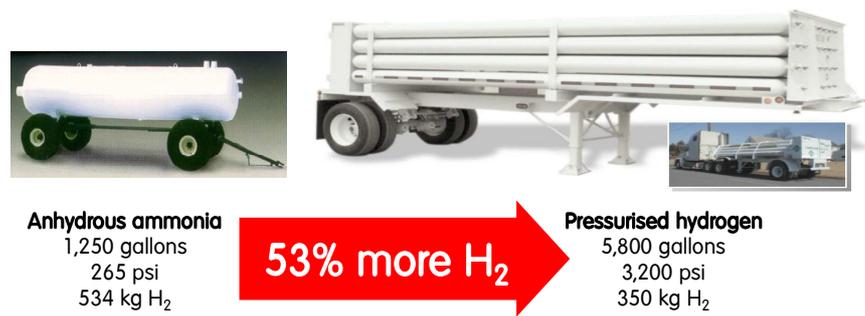


By comparison, the low volumetric energy density of hydrogen — in both compressed gas and liquid forms — makes the storage of hydrogen a difficult problem for most applications. This limitation is felt most strongly in the area of onboard storage, but it is also problematic in the delivery and distribution of hydrogen. As noted by the U.S. Department of Energy:

“Relatively small amount of gaseous hydrogen can be transported short distances by high pressure (2,640 psi) tube trailer. A modern high-pressure tube trailer is capable of transporting approximately 300-400 kg of hydrogen. Unfortunately, this method of hydrogen delivery is expensive for distributing hydrogen as a transportation fuel.”

The transportation of hydrogen via anhydrous ammonia tanks and ultra-high pressure tube trailers is compared below. On the left is a non-regulated agricultural nurse tank. Pressurised to 265 psi, this contains 3,025 kg of ammonia, of which 17.6% (534 kg) is hydrogen. On the right is a 5,800 gallon tube trailer. Pressurised to 3,200 psi, this contains 350 kg of pure hydrogen gas. Less than a quarter of size, the humble ammonia nurse tank contains 53% more hydrogen than the high-pressure tubes.

Figure 2: Anhydrous ammonia and pressurised hydrogen transportation



Easily reformed

Ammonia has a lower volumetric energy density (MJ/litre) than most liquid fuels. However, after subtracting the energy required to elicit hydrogen from each fuel, ammonia emerges with the highest net energy density of all existing and candidate fuels. Furthermore, except hydrogen itself, ammonia is the *only* fuel that does not contain carbon.

Figure 3: Volumetric energy density of fuels before and after reforming

Fuel	Base MJ/litre	Reformed MJ/litre
H ₂ (5,000 psi)	4.0	4.0
H ₂ (liquid)	9.9	9.9
NH ₃ (liquid)	15.3	13.6
Methanol	17.9	10.2
Ethanol	23.4	9.1
Propane (liquid)	29.4	8.6
Gasoline	36.2	9.2
JP-8	40.5	9.7

Stable long-term storage

Hydrogen gas molecules are smaller than all other gases, and they can diffuse through many materials otherwise considered airtight or impermeable. For this reason hydrogen must be stored in bulky fibre-composite, high-pressure vessels. Furthermore, metals such as ferrite steel are susceptible to degradation and cracking due to a phenomenon called hydrogen embrittlement. For these and other reasons a gaseous hydrogen plumbing system that is truly leak-free is nearly impossible to build without all welded joints.

By comparison, many polymers are compatible with ammonia, so it is likely that composite tanks or lightweight aluminium tanks with polymer liners could be used for onboard storage of ammonia. As noted elsewhere in this report, dilute ammonia solutions (5-10%) are sold around the world in simple plastic bottles. Furthermore, reinforced rubber is impervious to anhydrous ammonia, enabling lightweight and inexpensive tubes to be used for transferring the substance from one vessel to another.

Density

Liquid anhydrous ammonia expands 850 times when released to ambient air and can form large vapour clouds. These clouds are normally lighter than air and will rise. Accidental ammonia leaks therefore tend to disperse quickly, thereby reducing the threat of intoxication. However, liquid anhydrous ammonia may also form an aerosol which means that some of it may form small liquid droplets. As an aerosol, the droplets of ammonia are heavy and sink toward the ground.

Anhydrous ammonia may also cause water vapour to condense in the air forming a visible white cloud. Therefore, when anhydrous ammonia is released to the air, it may rise and disperse as a gas or it may be heavy and travel along the ground as an aerosol or because it has trapped water vapour. In either case, the cloud may remain low instead of rising into the air.

Figure 4: Physical properties of ammonia and other alternative fuels

		Air	Ammonia	Hydrogen	Gasoline	Methanol	Methane
Boiling point	°C	-	-33.4°C	-252°C	100-400°F	64.7°C	-161°C
Density (gas)	Kg/m ³	1.20	0.889	0.089	-	-	0.717
Solubility in water	mg/100 ml	-	89.9	-		Miscible	3.5

The influence of ambient temperature and humidity levels on the ammonia evaporation rate is evident in documented ammonia spillages. In one incident, when the weather was dry and air temperature about 27°C, the toxic cloud resulting from a 1,300 gallon ammonia leak dispersed within 12 minutes. By contrast, in January 2002, when 146,200 gallons of ammonia were spilt on a cold and foggy day, the resultant noxious cloud rose 300 feet into the air and expanded 5 miles downwind of the accident site to cover a population of 11,600 people. The persistence of the ammonia cloud was attributed to a localised temperature inversion at the time of the accident.

Easily detectable

Humans can smell anhydrous ammonia at 3 to 5 ppm – 100 times lower than the alarmingly labelled “immediately dangerous to life of death” (IDLH) concentration stipulated by the National Institute for Occupational Safety and Health (NIOSH).

Undeniably offensive at higher strengths, its characteristic smell provides an invaluable early warning of potentially lethal emissions. In contrast, odourless gases such as methane must be blended with foul-smelling mercaptan to signal its presence. Worse still, the odourless “silent killer” carbon monoxide unintentionally kills over 20 people in the United Kingdom and over 500 people in the United States every year.

For these reasons the pungent and undisputedly odious smell of concentrated ammonia should be celebrated as a free and natural warning system for the presence of this non-flammable yet toxic gas.

The health and safety benefits of ammonia’s pungency are well noted by industry experts:

Health & Safety Executive (UK): *“Under normal circumstances people will not be able to bear ammonia concentrations at even a fraction of the flammable limit.”*

European Fertilizer Association: *“Ammonia can be smelled at very low concentrations. Some people can smell ammonia even at a concentration of 5 ppm. Most people smell ammonia at concentrations between 20 and 50 ppm which are far below the life threatening concentration levels.”*

GreenPeace: *Ammonia is toxic, but has a characteristic, sharp smell which gives a warning below concentration levels that endanger health.*

Easily liquefied

Unlike hydrogen, anhydrous ammonia is easily liquefied and can be transported under moderate pressure.

Manufacturing

Ammonia is unique as a fuel since it neither contains carbon nor necessarily produces carbon during its manufacture. Furthermore it can be produced renewably, or electrochemically, or organically, or biologically. These and other methods provide a succession of carbon-free manufacturing routes that can be developed and adopted in accordance with evolving market demands and economics. Existing ammonia manufacturing techniques, namely methane reforming, can be modified to cut CO₂ emissions by 77% compared to gasoline. Ultimately, however, ammonia produced from renewable hydrogen, or directly via anaerobic digestion or biological processes, would eliminate carbon dioxide emissions entirely.

Natural gas

About 85% of world ammonia production is based on steam reforming of natural gas. Hydrogen produced by reformed methane is reacted at high temperature and pressure with nitrogen according to the formula $N_2+3H_2\rightarrow 2NH_3$ to create anhydrous ammonia. This latter step is the well known Haber Bosch process.

The typical inputs, outputs, and atmospheric emission levels of modern ammonia plants are detailed below. It can be seen that conventional steam reforming plants generate 1.15-1.30 tonnes CO₂ per tonne of NH₃ plus 0.5 tonnes CO₂ per tonne of NH₃ in atmospheric emissions.

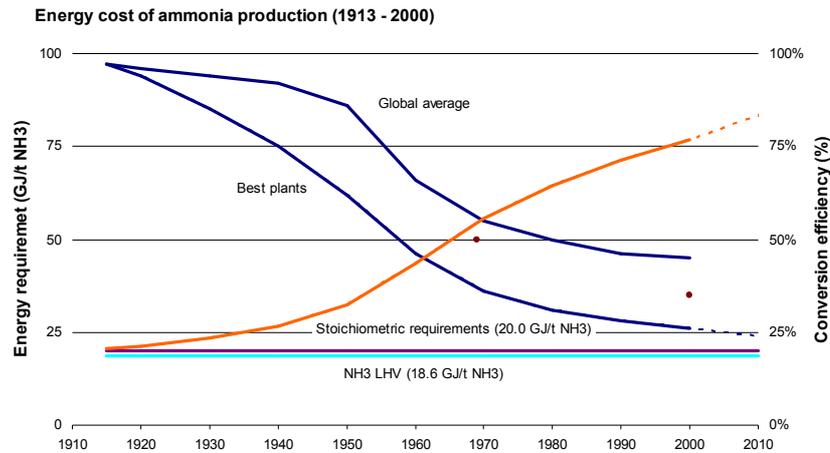
Figure 5: Ammonia refineries inputs, outputs, and flue emissions

		Conventional reforming	Excess air reforming	Partial oxidation
Inputs				
Total energy	GJ/t NH ₃	32-35	32-35	39-45
-Feedstock	GJ/t NH ₃	24.5	26.0	32.0
-Fuel	GJ/t NH ₃	8-10	6-8	-
Water	t/t NH ₃	0.7-1.5	0.7-1.5	1.2
Air	t/t NH ₃	1.1	1.6	4.0
Outputs				
-Ammonia	t/d	1,000-1,500	1,000-1,500	1,000-1,500
-Carbon dioxide	t/t NH ₃	1.15-1.30	1.15-1.30	2.0-2.6
Atmospheric emissions				
CO ₂	t/t NH ₃	0.5	0.4-0.5	n.a.
NO _x	kg NO ₂ /t NH ₃	0.6-1.3	0.6-1.3	-
SO ₂	kg/t NH ₃	<0.01	<0.01	1-3
CO	kg/t NH ₃	<0.03	<0.03	<0.13

Ammonia is produced today in large petrochemical plants. Costing \$150m to \$250m these are capable of producing 400,000 to 800,000 tonnes of ammonia per year.

Unlike many other hydrogen storage technologies, which typically are in an embryonic stage of development, ammonia has benefited from a hundred years of manufacturing improvements. Modern refineries are over 75% efficient and incremental productivity gains can be expected as catalytic and waste heat recovery techniques are improved.

Figure 6: Ammonia production energy requirements and efficiency



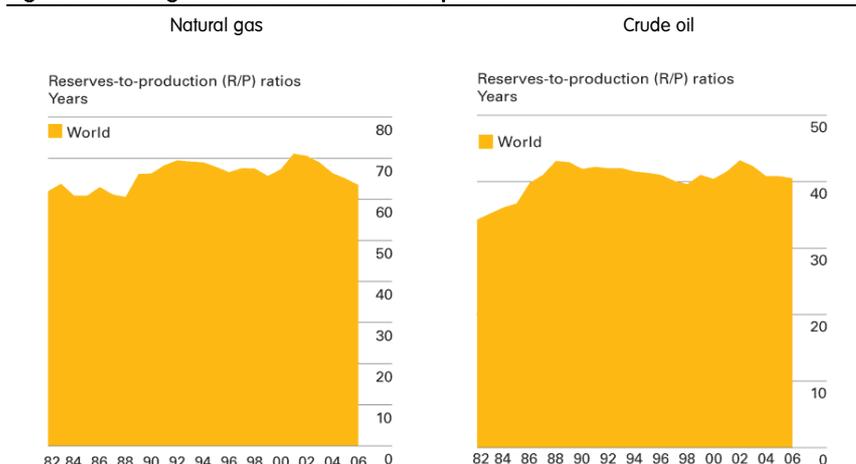
Over 120 million tons of anhydrous ammonia are produced every year. Although representing a small fraction of worldwide automotive energy requirements, these facilities serve to establish the economic viability of industrial-scale ammonia production. It is worthwhile noting that China and India, both destined to rank among the world's largest automotive markets, are also largest producers of anhydrous ammonia.

Figure 7: Annual ammonia production by nation (thousand metric tonnes)

	1994	1996	1998	2000	2002	2004	2006e
China	19,800	23,000	26,500	28,000	30,100	34,800	39,000
India	7,330	7,800	10,000	10,100	9,830	10,700	10,800
Russia	7,260	7,000	6,500	8,740	8,600	9,800	10,000
USA	13,400	13,200	14,700	12,300	10,800	8,850	7,900
Trinidad	1,650	1,800	2,270	2,690	3,300	3,880	5,200
Indonesia	3,010	2,870	3,600	4,000	4,200	4,120	4,400
Ukraine	3,000	3,000	3,300	3,300	3,700	3,900	4,300
Other	36,530	37,410	38,680	39,530	37,980	41,170	40,750
Total	91,980	96,080	105,550	108,660	108,510	117,220	122,350

According to the BP Statistic Review of World Energy 2007, the reserves-to-production ratio of natural gas was 63.3 years compared to 40.5 years for oil. Concludes BP: "The global natural gas R/P ratio remained [in 2006] well above the oil R/P ratio". Such statistics suggest the transition from oil to gas-derived ammonia would extend — as a transportation fuel — the lifetime of proven resources.

Figure 8: Natural gas and crude oil reserves-to-production rates (1982-2006)



Renewable

Electrical power produced by renewable sources such as wind, solar, hydroelectric, and ocean thermal energy conversion (OTEC) can be used to electrolyse hydrogen from water or brine solutions. Compared to steam reformed hydrocarbons, hydrogen produced by water electrolysis has high purity level. For this reason high-temperature “scrubbing” steps are not required and therefore schemes for renewably producing ammonia can be small compared to natural gas refineries.

With renewable energy sources commonly located in remote locations, ammonia represents a viable method for transporting “liquefied electricity” to distribution hubs or direct to refuelling stations.

Electrochemical

Solid state ammonia synthesis is an emerging technique for manufacturing ammonia electrochemically from water and air. Hydrogen atoms, obtained from water (steam) decomposition at the anode, are stripped of electrons and conducted (as protons) through a proton-conducting ceramic electrolyte. Emerging at the cathode, the protons regain electrons and react with adsorbed dissociated nitrogen atoms to form NH_3 .

Conceivable advantages of this approach, which is the subject of a patent application by its inventors, NHThree LLC, include the elimination of costly and energy-intensive electrolyzers, and the high-pressure reactors used during the Haber Bosch process.

Organic digestion

Anaerobic digestion is the breakdown of organic material in the absence of oxygen. “Bio-ammonia” can be produced directly during the digestive process in the form of ammonium ions (NH_4^+) and dissolved ammonia gas (NH_3), or indirectly via the digestion or pyrolysis of biomass into syngas ($\text{CO} + \text{H}_2$).

Studies have shown that low doses of ammonia-nitrogen are beneficial to organic decomposition, whilst higher concentrations quickly deteriorate the anaerobic process. To maximise digestive efficiency, operators monitor ammonia levels and siphon off excess amounts when necessary. Whilst some excess ammonia can be discharged as a fertilizer, the oversupply of nutrients to water resources is a major environmental problem.

Figure 9: Effects of bio-ammonia on anaerobic digestion

Ammonia nitrogen (NH ₃ -N) concentration	Effect of ammonia nitrogen on anaerobic digestion
50-200	Beneficial
200-300	No adverse effects
1,500-3,000	Inhibitory at pH over 7.4 to 7.6 standard units
Above 3,000	Toxic

The anaerobic digestion process can be modified to promote ammonia production. A good candidate for making bio-ammonia would be sweet sorghum. It has been estimated that an acre of sweet sorghum could be converted to 1,850 gallons of liquid ammonia with a total energy content of 95 million Btu. This would be compared to ethanol from an acre of corn which would produce 560 gallons of ethanol with a total energy content of 44 million Btu, or 1,185 gallons of ethanol from an acre of cellulosic biomass with a total energy content of 93 million Btu.

Bio-ethanol contains 52% carbon by weight, whereas the ammonia contains zero carbon. Ensiled sorghum is easy to store for extended periods of time and is highly digestible (over 90%) in an anaerobic digester. Production costs and fertilizer usage would also be lower for crops like sorghum than for corn.

Biological nitrogen fixation

Nitrogen is a necessary element for all living organisms. Living cells contain up to 14% nitrogen, which forms an essential part of several key cell components, such as protein and DNA. However, even though nitrogen gas makes up around 79% of the atmosphere, it is chemically extremely inert, and generally unavailable to living microorganisms.

The ability for some bacteria and actinomycetes to *biologically* convert atmospheric nitrogen into NH₃ has fascinated botanists and biochemists for centuries. Yet it was not until the 1880's that scientists generally accepted the reality of this apparently miraculous process.

Cyanobacteria, also known as cyanophyta or blue-green algae, is a particularly important source of biological ammonia. Having inhabited much of the surface of the earth for billions of years, this organism is responsible for a significant proportion of biological nitrogen fixation both in the oceans and on land.

In his time, no one was more acutely aware of the possibility of biological nitrogen fixation than Fritz Haber himself. In concluding his 1920 Nobel Prize acceptance speech, he noted:

"It may be that this solution [the Haber process] is not the final one. Nitrogen bacteria teach us that Nature, with her sophisticated forms of the chemistry of living matter, still understands and utilizes methods which we do not yet know how to imitate."

Yet in stark and shameful contrast to the bio-ethanol industry, the biological nitrogen fixation industry has struggled to grow beyond its academic origins due partly to under investment by governmental and commercial agencies. The challenges ahead appear daunting, but with concerted effort it may be possible to industrialise the nitrogen cycle itself, and thereby free ourselves from the grip of hydrocarbon dependency.

Transportation

Anhydrous ammonia is distributed today via an international network of pipelines, railroads, barges, ships, road trailers, and storage depots. Although designed to serve the needs of the fertilizer and chemical industries, such facilities illustrate the feasibility of safely and efficiently transporting huge quantities of this carbon-free fuel from remote production sites to local markets.

The global ammonia network has also created an international community of auxiliary industries comprising design engineers, health and safety advisors, component manufacturers, spare part suppliers, ammonia sensor vendors, and emergency responders, all expertly trained in the nuances of anhydrous ammonia storage and distribution.

Pipelines

Ammonia is safely and cost effectively transported via vast pipelines. In the United States, the NuStar line (3,070 km) pumps anhydrous ammonia from the Mississippi delta and the Texas and Oklahoma panhandle region, into the heart of the corn belt, where it is distributed further by the Magellan line (1,100 miles). In Eastern Europe, the Odessa line (2,400 km) pumps anhydrous ammonia from the Black Sea port to fertilizer and chemical plants throughout the Baltic region.

Railroads

Every year more than 1.5 million tonnes of anhydrous ammonia are hauled by railway across Western Europe alone. An even greater quantity is transported in the United States using DOT 105J insulated tank cars, each storing 33,500 gallons of liquid anhydrous ammonia. In both regions, however, rail shipments are declining as transporters seek to reduce the risk of transporting hazardous substances (this is not specific to NH₃ but applies to all hazmats).

Barges

Without access to a network of long-distance pipelines, many West European importers use river barges, each capable of carrying around 1,000 tonnes of anhydrous ammonia, to transport the chemical around the region.

Road trailers

Ammonia is easily liquefied under moderate pressure (14 bar) and transported in 4-tonne trailers. These are identical in size and construction to those used to safely and efficiently distribute LPG by road. Due to its smaller higher heating value (HHV), double the number of tankers would be required to deliver the same amount of energy as an equivalent gasoline container. By comparison, over 15 high-pressure hydrogen containers would be required to fulfil the same requirements – one every hour for an average refilling station.

Figure 10: Refuelling logistics for alternative fuels

	Units	H ₂ Gas	Liquid H ₂	Methanol	Propane	Gasoline	Ammonia
Pressure	bar	200	1	1	5	1	4
Weight to customer	kg	40000	30000	40000	40000	40000	40000
Weight from customer	kg	39600	27900	14000	20000	14000	14000
Delivered weight	kg	400	2100	26000	20000	26000	26000
HHV of fuel	MJ/kg	141.9	141.9	23.3	50.4	48.1	22.5
HHV energy per truck	GJ	56.8	298.0	605.8	1008.0	1250.6	585.0
Relative to gasoline	x	0.045	0.238	0.484	0.806	1	0.468
Diesel consumed	kg	79.6	57.9	54	60	54	54
Diesel HHV energy	GJ	3.56	2.59	2.41	2.68	2.41	2.41
Energy consumed/HHV energy	%	6.27	0.87	0.40	0.27	0.19	0.41
Relative to gasoline	x	32.5	4.5	2.1	1.4	1.0	2.1
H ₂ -efficiency factor	x	0.7	0.7	1	1	1	1
HHV energy delivered	GJ/d	875	875	1251	1251	1251	1251
No. trucks for same no. of serviced cars	#	15.4	2.9	2.1	1.2	1	2.1

Nurse tanks

According to the Fertilizer Institute, an estimated 200,000 nurse tanks are in service across the United States. These apply between 1.0 million and 1.5 million loads of anhydrous ammonia to fields annually. Because they are not required to be removed from service at a given age, many nurse tanks that have received no effective safety inspections for several decades remain in use on farms and at filling facilities.

Plastic bottles

Household ammonia, typically 5-10% aqueous solution, is distributed worldwide in non-pressurised plastic bottles. Although unsuitable as an automotive fuel, such dilutions may satisfy the energy requirements of less demanding applications, such as portable power generators.

Environmental issues

Ammonia itself has neither ozone depletion potential (ODP = 0) nor global warming potential (GWP = 0). Furthermore, since it contains no carbon, the burning of NH₃ in an internal combustion engine or fuel cell produces no CO₂. Depending on the production method, however, greenhouse gases *are* emitted during ammonia manufacture and these must be evaluated in a World-to-wheel™ analysis of this alternative fuel.

Carbon dioxide

The *combustion* of 1 gallon of gasoline produces 8.8 kg of CO₂. By comparison, the *production* of 1 gallon of anhydrous ammonia from natural gas (CH₄) produces 2.8 kg of the greenhouse gas. Adding contributions from feedstock extraction and fugitive releases, the total greenhouse gas production rate is 10.2 kg and 4.1 kg CO₂ per gallon of gasoline and ammonia respectively.

Normalising these results by their respective heat values, the World-to-wheel™ emission from gasoline and ammonia is 75.7 kg-CO₂/GJ and 78.4 kg-CO₂/GJ respectively. In other words, the combustion of ammonia, when derived from clean natural gas, produces 4% *more* CO₂ emissions than the equivalent calorific quantity of gasoline.

Heavier feedstocks such as petroleum coke generate significantly more CO₂ than natural gas. For example, the combustion of ammonia produced via the partial oxidation of complex hydrocarbons such as coal would generate twice the amount of CO₂ than gasoline or diesel. This result is

worse than the extraction of gasoline from Canadian tar sands and is not considered an environmentally viable option.

Figure 11: Logistics of gasoline and alternative fuel delivery

Fuel		Gasoline <i>Crude oil</i>	Gasoline <i>Tar sands</i>	Diesel <i>Crude oil</i>	Ammonia <i>Natural gas</i>	Ammonia <i>Petroleum coke</i>
<i>CO₂ emissions</i>						
Extraction	<i>kg/gal</i>	0.6	2.7	0.7	0.2	0.4
Refining	<i>kg/gal</i>	0.4	0.4	0.5	3.7	8.3
Fugitive	<i>kg/gal</i>	0.4	0.4	0.4	0.2	0.5
Combustion	<i>kg/gal</i>	8.8	8.8	10.1	0.0	0.0
Total		10.2	12.2	11.7	4.1	9.2
HHV	<i>MJ/kg</i>	48.1	48.1	44.7	22.5	22.5
Density	<i>kg/liter</i>	0.74	0.74	0.85	0.61	0.61
HHV	<i>MJ/liter</i>	35.6	35.6	38.0	13.7	13.7
HHV	<i>MJ/gal</i>	134.9	134.9	144.0	52.0	52.0
CO ₂ per MJ	<i>kg/MJ</i>	0.08	0.09	0.08	0.08	0.18
CO ₂ per GJ	<i>kg/GJ</i>	75.7	90.8	81.4	78.9	176.0
Compared to Gasoline	<i>X</i>	1.00	1.20	1.08	1.04	2.33

Irrespective of the hydrocarbon feedstock or manufacturing method, CO₂ emissions produced at an ammonia refinery are amenable to sequestration or reuse in other products. Retained or otherwise converted, such techniques would reduce World-to-wheel™ CO₂ emissions from an ammonia-fuelled combustion engine to 24.7 kg-CO₂/GJ – a 77% reduction compared to gasoline tailpipe emissions.

Depleted natural gas wells appear particularly well suited to the sequestration of CO₂ since one volume of natural gas produces an equal volume of CO₂. This is unlike oil or coal where the volume of CO₂ produced is significantly greater than the original carbonaceous fuel. The fact CO₂ is not today captured at ammonia refineries can be understood (though not entirely excused) by the fact that ammonia and urea production represents only 0.3% of total CO₂ emissions in the United States.

NO_x

What about NO_x emissions? Considering nitrous oxide (N₂O) is 300 times more potent as a greenhouse gas than CO₂, it is imperative that ammonia ICEs do not spoil their carbon-free credentials by wreaking environmental damage via ruinous N₂O or nitrogen dioxide (NO₂) emissions.

Studies conducted during the 1970's showed that the NO_x emissions from ammonia-fuelled ICEs (without after treatment) is about a quarter of that from an equivalent gasoline engine (with after treatment). The results of more recent ammonia engine trials by the Hydrogen Engine Center have not yet been published though preliminary reports say the unit "has run even better than anticipated".

In any case, NO_x emissions can be removed readily using a two-way catalyst that combines uncombusted NH₃ and NO_x to form benign N₂ and H₂O water via the reaction 6NO + 4NH₃ → 5N₂ + 6H₂O. Such catalysts exist today and are used routinely to clean NO_x from diesel exhaust. Indeed, a catalyst might not even be necessary, since during NH₃ combustion NH₃ and NO_x are in contact at elevated temperatures where catalysts are not needed for the reaction to go forward.

Alternatively, ammonia itself can be used as a highly effective reagent for reducing NO_x into nitrogen gas and water. Honda and DaimlerChrysler have already launched ammonia-based deNO_x systems. Denied access to an onboard source of NH₃, the reagent must either be produced catalytically or extracted from urea derivatives such as AdBlue. Alternatively, Delphi proposes an onboard ammonia generator featuring a diesel fuel reformer.

Overall, compared to gasoline, anhydrous ammonia would generate a slight increase (+4%) in CO₂ emissions when produced using natural gas *without* centralised CO₂ capture, though a significant reduction (-77%) where sequestration is adopted. Regards NO_x, further information is required before any robust conclusion can be drawn, though even in a worse-case scenario the availability of on-board NH₃ would provide a straightforward method of eliminating residual NO emissions.

Energy economics

The wholesale price of anhydrous ammonia is dominated by the price and consumption of feedstock, the most important being natural gas. Ammonia therefore tends to be produced in low-cost areas, such as the Arabian Gulf and Trinidad & Tobago, and shipped to high-price areas, such as Western Europe and North American.

In the United States, higher natural gas prices have resulted in a gradual reduction in domestically produced ammonia. In 2006, local production was 7,900 million tonnes, down 46% from its peak in 1998. Over the same period, the net import reliance as a percentage of apparent consumption increased from 18% to 42%.

Notwithstanding renewable or bio-ammonia, the adoption of ammonia as a hydrogen carrier or hydrocarbon replacement would do little to ameliorate the U.S.'s dependence on foreign energy reserves. However, unlike petroleum, ammonia can be produced using renewable energy sources, while the origins of U.S. ammonia imports are also different.

Figure 12: U.S. Ammonia and gasoline production and net importers

	Ammonia	Petroleum
Apparent consumption	13,600 thousand tonnes	20.8 million barrels per day
Domestic production	7,900 thousand tonnes	6.9 million barrels per day
Refinery utilisation	80%	89.7%
Net imports as % of consumption	42.0%	59.6%
Import countries	Trinidad & Tobago (54%) Canada (17%) Russia (13%) Ukraine (7%) Other (9%)	Persian Gulf (18%) Canada (17%) Saudi Arabia (12%) Mexico (12%) Venezuela (11%) Nigeria (9%) Other (21%)

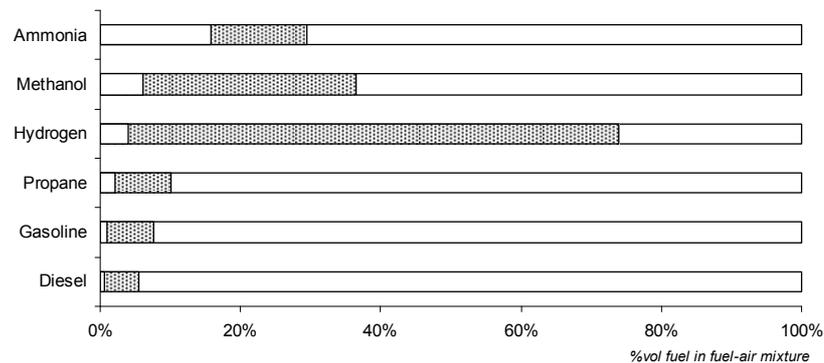
Risks: Flammability

Ammonia is extremely difficult to ignite. The U.S. Department of Transportation officially classifies the substance as non-flammable, while in his 1937 patent on ammonia refrigeration, Albert Einstein described NH₃ as "an inert gas".

The primary cause of ammonia's inertness is its narrow range of combustible fuel-to-air ratios. Fuel and air will burn only if the concentration of fuel is between an upper and lower flammability limit. With a lower flammability limit (LFL) of 16%, the concentration of ammonia required to sustain combustion is 11 times more than hydrocarbons such as gasoline and diesel. By comparison, hydrogen has a LFL of 4.1% but an UFL of 74% - the widest flammability range of any existing or prospective transportation fuel.

Although pure ammonia vapours are not flammable at concentrations of less than 16%, studies have found the lower flammability limit of ammonia can be 8% if contaminated with lubricating oil, depending on the type and concentration of oil.

Figure 13: Flammability range of alternative fuels



Another useful gauge for the flammability of ammonia is its minimum ignition energy (MIE). At 680 mJ the MIE is 1,000 times greater than gasoline and diesel, and 10,000 times greater than hydrogen. Indeed the MIE of ammonia is higher than almost every known combustible substance, including coffee dust and grass seed.

Considering an electrostatic spark from the human body releases about 10 mJ, it is unsurprising that the Petroleum Equipment Institute has received over 170 reports of injurious fires attributed to static discharge at gasoline fuelling stations across the United States alone. The actual figure including unreported instances may be considerably larger.

For these and other reasons it is extremely rare for ammonia to catch fire. As noted by the UK Health & Safety Executive: *"There have however been very few incentive explosions involving ammonia compressor houses in the UK."*

Risks: Toxicity

More than any other factor, concerns regarding the toxicity of ammonia have inhibited its adoption as a hydrogen carrier or gasoline replacement. By most measures such concerns seem well founded: ammonia truly is an unpleasant substance and – like all fuels – must be handled with due care and respect.

Human health

Anhydrous ammonia is hygroscopic, which means that it seeks water from the nearest source, including the human body. This attraction places the eyes, lungs, and skin at greatest risk because of their high moisture

content. Caustic burns result when the anhydrous ammonia dissolves into body tissue.

Most deaths from anhydrous ammonia are caused by severe damage to the throat and lungs from a direct blast to the face. When large amounts are inhaled, the throat swells shut and victims suffocate. Exposure to vapours or liquid also can, unless dowsed copiously with water, cause blindness.

The recommended long-term exposure limit for ammonia is 25 ppm, 8 hour time weighted average (TWA), and the short-term exposure limit is 35 ppm, 10 minute TWA. At 400 ppm – a concentration 10 to 100 times higher than humanly detectable – most people experience immediate nose and throat irritation, but suffer no permanent ill-effects after 30-60 minutes exposure. A level of 700 ppm causes immediate irritation to the eyes, and a level of 1,700 ppm will give rise to repeated coughing and can be fatal after about 30 minutes exposure. Exposure to concentrations exceeding 5,000 ppm for quite short periods can result in death.

Figure 14: Exposure limits of anhydrous ammonia

Exposure	Effect on the body	Permissible exposure
3-5 ppm	Least detectable odour	No injury from prolonged or repeated exposure
20-50 ppm	Detectable by most people	No injury from prolonged or repeated exposure
134 ppm	Irritation of nose and throat	Eight hours, maximum exposure
700 ppm	Coughing, severe eye irritation, may lead to loss of sight	One hour, maximum exposure
1,700 ppm	Serious lung damage, death unless treated.	No exposure permissible.
2,000 ppm	Serious edema, strangulation, asphyxia	No exposure permissible
5,000 ppm	Suffocation within minutes	No exposure permissible
10,000 ppm	Immediately fatal	No exposure permissible

The multiplicative importance of exposure *severity* and *duration* is evident in the official accident report following the derailment of five ammonia tanks near Minot, North Dakota, in January 2002. Over 146,700 gallons of anhydrous ammonia were released within 400 metres of the Tierracita Vallejo community. According to the report:

At least three residents of the Tierracita Vallejo neighborhood sustained serious injuries as a result of the accident. All of these persons left the protective confines of their homes and were directly exposed to the anhydrous ammonia cloud for a prolonged period of time, resulting in their serious injuries. The cloud of anhydrous ammonia was fog-like and very thick, with witnesses reporting almost no visibility through the cloud. Once the persons were inside the anhydrous ammonia cloud, the poor visibility disoriented them and contributed to their prolonged exposure to the anhydrous ammonia.

One Tierracita Vallejo resident died following the ammonia spillage when he crashed his car in an attempt to escape the impenetrable toxic cloud. Incapacitated by his injuries, he died from ammonia asphyxiation while emergency workers waited beyond a cordon for the cloud to disperse. In total, 11 people sustained serious injuries, and 322 people, including the two train crew members, were seen by medical personnel.

An additional concern is the low boiling point of anhydrous ammonia. The chemical freezes on contact at room temperature. It causes burns similar to, but more severe than, those caused by dry ice.

Overall, anhydrous ammonia is extremely dangerous to human health, albeit at concentrations 100 times higher than most people can detect. Important safety and liability issues would need to be resolved if ammonia

were to be used as a hydrogen carrier or direct gasoline replacement. Most importantly, standards governing its storage and transportation would need to be upgraded before its adoption as a gasoline replacement. However, this is no more a feat than already overcome successfully by gasoline itself, and other combustible fuels such as natural gas and the lithium compounds used in rechargeable batteries.

Exhaust emissions

Whilst it might be argued that *accidental* releases of anhydrous ammonia present a greater toxicity hazard than comparable quantities of gasoline or diesel, the same can not be said about the *unavoidable* combustion by-products of each fuel.

In an internal combustion engine, ammonia is converted primarily into nitrogen and water via the reaction $4\text{NH}_3 + 3\text{O}_2 \rightarrow 2\text{N}_2 + 6\text{H}_2\text{O}$. Both products are environmentally and biologically benign and can be vented freely into the atmosphere.

By comparison, the exhaust products of gasoline and diesel engines consist of gaseous and particulate fractions, many of which are *extremely* dangerous to human life. Diesels exhausts are known to contain over 40 air contaminants recognised as toxicants, carcinogens, reproductive and developmental hazards, and endocrine disrupters. The EPA conservatively estimates that diesel exhaust particulates are responsible for over 125,000 lifetime cancers in the metropolitan centres of the United States alone.

Overall, the comparative health hazards presented by anhydrous ammonia and hydrocarbon fuels create an awkward dilemma. On the one hand, *unintentional* ammonia spillages may present a *localised* hazard yet its combustion products are benign. On the other, gasoline and diesel present lesser – though not negligible – transportation hazards while their tailpipe exhausts *unavoidably* are toxic, carcinogenic, and *non-containable*. The choice is stark but irrefutable.

Safety record

According to FACTS, the most comprehensive database of industrial accidents in the world, anhydrous ammonia has been implicated in 235 incidents of which 35 were fatal. Over the same period, hydrogen has been responsible for 394 incidents of which 73 involved fatalities.

The vast majority of accidents and deaths caused by anhydrous ammonia spillages have occurred in the United States, where the substance is spread directly onto fields by farmers using non-regulated equipment that commonly is over 30 years old. In Europe, FACTS records only one fatal accident involving anhydrous ammonia; this occurred in 1976 when the substance was being offloaded at a Swedish shipping port.

The infrequency of fatal ammonia accidents can not be explained by any scarcity arguments: it is the second most widely produced and distributed inorganic substance in the world (the first is sulphuric acid). Over 120 million tonnes are produced every year for applications including fertilizer production, pulp & paper manufacturing, pharmaceuticals, mining, explosives and speciality chemicals. The most widespread non-fertilizer use is industrial refrigeration and cleaning.

Hydrogen similarly is used as an auxiliary agent in a multitude of manufacturing industries including float glass production, metallurgy, fat hardening, chemical production, semiconductor processing and generator cooling. However, with an estimated global production rate of 4 million tonnes per year, the quantity of hydrogen gas stored and distributed is

miniscule compared anhydrous ammonia. Furthermore, while hydrogen tends to be used in specialist industries with commensurably high levels of regulation and training, ammonia is a commodity substance found in most industrial refrigeration and manufacturing plants around the world.

Figure 15: Industrial accidents involving ammonia and hydrogen

Country	Records kept since	Accidents involving					
		Ammonia....		...of which anhydrous ammonia		Hydrogen	
		<i>Incidents</i>	<i>Fatal</i>	<i>Incidents</i>	<i>Fatal</i>	<i>Incidents</i>	<i>Fatal</i>
Australia	1920	10	0	15	0	5	0
Canada	1917	20	2	12	0	18	2
China	1978	11	6	NR	NR	NR	NR
France	1905	28	3	3	0	35	4
Germany	1900	57	4	3	0	45	8
India	1944	16	3	1	0	8	3
Italy	1907	8	2	0	0	8	3
Japan	1922	8	2	0	0	13	5
Mexico	1950	11	7	1	1	1	0
Netherlands	1807	123	2	1	0	67	4
Russia	1992	5	3	0	0	1	0
Spain	1958	0	0	0	0	2	0
Sweden	1864	3	0	1	1	1	1
UK	1879	48	7	4	0	24	4
USA	1873	199	24	186	30	114	23
Other		302	22	8	3	52	16
Total		650	87	235	35	394	73
Worldwide circulation (million tonnes)					150		4

NR=Not reported

Accidents involving ammonia, ammonia solutions, and ammonia compounds are more common. The FACTS database describes 650 such incidents of which 87 were fatal. However, these statistics are a less reliable measure of ammonia toxicity since the database entries typically implicate ammonia alongside other hazardous chemicals such as methane, propane, hydrogen sulphide, phosphoric acid, sulphuric acid, and ammonium chloride. Thus it is harder to attribute such accidents or their effects to ammonia alone.

Overall, the FIND database supports the view that anhydrous ammonia is a hazardous substance. However, it is essential to consider these statistics in the context of (a) its worldwide use as a commodity fertilizer and chemical, and (b) the rigour and appropriateness of regulations now governing its storage, distribution, and application. Indeed, when normalised by their respective quantities, ammonia appears less dangerous to human health than hydrogen. Such observations suggest that, subject to the upgrading of technical and regulatory standards, ammonia could be rendered "fit for purpose" as a hydrogen carrier or direct gasoline replacement.

Ecotoxicity

Accidentally released ammonia vapour dissipates by reacting with moisture in the air to form ammonium and eventually return to earth in rainfall. Precipitated ammonium rarely accumulates in soil because bacteria rapidly convert the ammonium not taken up by plant roots into nitrates (via nitrification). Nitrates can also be absorbed by roots or may leach through the soil profile. Fortunately, unlike crude oil spillages, ammonia does not concentrate in the food chain.

Ammonia is harmful to aquatic life if present at sufficiently high concentrations. In addition, it is known to stimulate the growth of algae and other photosynthetic aquatic life, which can lead to eutrophication via excessive loss of available oxygen, and other undesirable changes in the aquatic ecological system.

In the event of an ammonia spillage into lakes or waterways, the ecological balance can be restored by exploiting biological mechanisms within the nitrogen cycle. More specifically, nitrogen removal from wastewater is achieved via denitrification, converting harmful ammonia to essentially harmless nitrogen gas.

Ammonia motors

Anhydrous ammonia can be converted into useful energy either directly, i.e. using an internal combustion engine or electrochemical fuel cell, or indirectly via decomposing into hydrogen. Theoretical World-to-wheel™ efficiencies for each process are compared below.

Figure 16: World-to-wheel comparison of alternative fuel efficiencies

Feedstock Fuel	Internal combustion engine			Fuel cell		
	Crude oil Gasoline	Natural gas Ammonia	H ₂ (electrolysis) Ammonia	Natural gas Ammonia	Crude oil Methanol	Natural gas H ₂ (liquid)
Production	97%	72%	56%	72%	65%	38%
Reformer	-	99%	99%	80%	76%	-
Motor	24%	30%	35%	-	-	-
Fuel cell	-	-	-	35%	40%	55%
Total	23%	21%	19%	20%	20%	21%

Internal combustion engine

Considering the non-flammability of anhydrous ammonia, it seems unlikely that this carbon-free substance is a viable fuel for the internal combustion engine. However, ammonia *can* be used successfully as a spark ignition engine fuel, at compression ratios comparable to hydrocarbon-fuelled engines, if (a) introduced as a vapour and (b) partially dissociated into hydrogen and nitrogen. Under such circumstances few engine modifications are necessary other than a means for flow control of the ammonia and adjustment of the spark timing.

The concentration of hydrogen injected into the fuel feed is a critical factor for successful operation of ammonia as a hydrocarbon replacement. Studies conducted in the mid-1960's showed the minimum concentration was in the range 4 to 5% by weight at intermediate engine speeds. More recent studies by the Hydrogen Engine Center have shown an ammonia-powered 6-cylinder engine running "flawlessly" on a combination of 95% anhydrous ammonia and 5% hydrogen. For automotive applications it may be prudent to generate and harvest excess hydrogen to facilitate cold starts and satisfy dynamic torque demands.

In spark-ignition mode, ammonia has a high octane rating (110-130). The specific fuel consumption using ammonia is double that of iso-octane at peak power, and 2.5 times the hydrocarbon at maximum economy. These values are comparable to the 2.1 times refuelling station frequency cited elsewhere in this report.

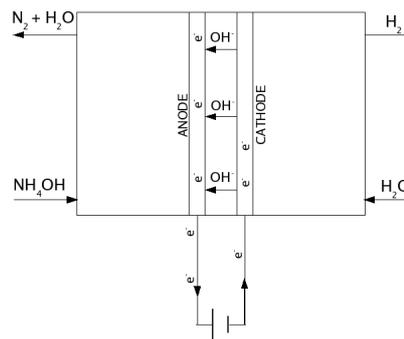
A somewhat more intriguing idea is the use of ammonia as a gasoline emulsificant. According to Professor Vito Agosta, Brooklyn Polytechnic University, ammoniated fuel can power an engine or burner with very little

modification. Similar to E15 bio-ethanol blends, the transition to an ammonia-based fuel economy can be as slow or as fast as societal conditions permit.

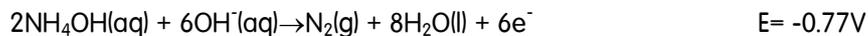
Ammonia electrolysis

Decomposition of ammonia into nitrogen and hydrogen has been studied since the early 1960's. More recent work at ACTA and Ohio University has confirmed the technical feasibility of efficiently reforming ammonia and converting the evolved hydrogen gas to electric power with a PEM fuel cell. The electrolysis of ammonia in an alkaline media is shown below.

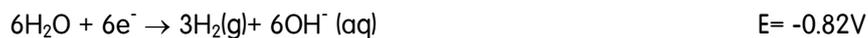
Figure 17: Ammonia electrolysis



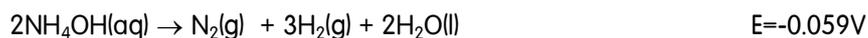
At the anodic side the hydroxyl ions (OH⁻) strip hydrogen atoms from ammonium hydroxide (i.e. ammonia in alkaline media) forming water, while the nitrogen atoms, adsorbed in the electrode surface, are oxidized to gaseous nitrogen (N₂) due to the positive potential that drains their electrons:



The cathodic side works exactly the same way as water electrolysis in alkaline media, the water molecules are broken into hydrogen and hydroxyl ions onto the electrode surface:



The overall reaction is:



Hydroxyl ions produced on the cathode side, pass through a membrane to reach the anodic side and be consumed, so the original concentration of KOH does not change with time. Commercially and operationally this is desirable since it eliminates the need to replenish the caustic KOH electrolyte.

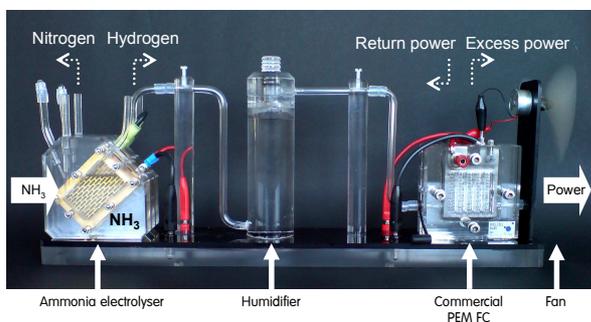
In theory, the electro-oxidation of ammonia has a Faraday efficiency of 100%. This is confirmed experimentally where efficiencies up to 99.24% are observed routinely and repeatedly. In terms of hydrogen productivity, preliminary electrolyser studies have yielded 15.19 ± 0.36 Wh/g H₂. This is 80% less than the 77.8 Wh/g H₂ required by commercial PEM water electrolyzers.

Figure 18: Experimental ammonia electrolysis results

Time (s)	300	600	300
Volume (mL)	2.85	5.9	2.98
Moles	1.18E-004	2.44E-004	1.23E-004
Efficiency	94.95%	98.28%	99.28%
Energy (Wh)	4.00E-03	8.00E-03	4.00E-03
Mass (g)	2.56E-04	5.31E-04	2.68E-04
Productivity (Wh/g)	15.60	15.07	14.92

The ability to use ammonia as a hydrogen carrier is demonstrated below. On the left is an alkaline ammonia electrolyser containing anhydrous ammonia and KOH electrolyte. Evolved hydrogen is fed to a commercial PEM via a water bath humidifier. Since less energy is required to electrolyse ammonia than contained in the resultant hydrogen gas, the PEM fuel cell produces net useful energy, in this instance used to power an electric fan.

Figure 19: transportable power generation using ammonia electrolysis



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Catalysts play a major role in the efficiency and durability of ammonia electrolysers. Generally speaking, both efficiency and robustness will increase with catalyst loading. However, with catalysts commonly made from platinum and other precious metals, the commercial viability of this hydrogen-producing design may be critically dependent on minimizing – or ultimately eliminating – platinum loadings. For this reason, any report on ammonia electrolysis must be normalised to account for the generosity or frugality of the catalyst loading.

The importance of minimizing catalyst costs was recently evidenced by the award of a \$960,000 contract to researchers at the University of Delaware. Using high-throughput screening methods, the Delaware academics will search systematically for low-cost, robust and active nano-catalysts that will enable efficient hydrogen production.

Ammonia cracking

Thermocatalytic decomposition of ammonia into hydrogen and nitrogen ($2\text{NH}_3 \Rightarrow 3\text{H}_2 + \text{N}_2$) is a well established process. The dissociation reaction is endothermic, requiring 2.69 MJ/kg of energy at 25°C. The heating value of dissociated ammonia, i.e. the H_2 and N_2 gases, is 21.5 MJ/kg, which means the maximum theoretical decomposition efficiency is 85.6%. Taking the energy requirements of fuel preheating and evaporation into account, the overall efficiency is in the range 80-83%.

Catalysts play a major role in thermocatalytic decomposition. Among metal catalysts, ruthenium and iridium are the most active for NH_3 dissociation under mild conditions. Other compounds that exhibit high activity for NH_3

cracking include alloys such as Fe-Al-K, Fe-Cr, La-Ni (-Pt) and La-Co (-Pt). In general, noble metal containing catalysts are not used in the commercial processes due to high cost. The supported Ni catalyst has been widely used in industry but the required ammonia dissociation temperature can be as high as 1000°C.

In general, temperatures over 400°C are required for stable ammonia dissociation. The reaction rate is increased at temperatures of 700°C or above, although dissociation can occur at temperatures as low as 300°C. Whilst practical for stationary applications, lower temperature operation may be required for on-board hydrogen generation due to cold-start requirements and dynamic power requirements.

Since the early 1980's researchers have developed ammonia cracking reactors for on-demand hydrogen generators. However, to satisfy the requirements of onboard hydrogen generation, the operating pressures and temperatures of these systems are considered extremely challenging.

Ammonia fuel cells

The basic technology for constructing both direct and indirect ammonia/air fuel cells capable of converting 37-47% of the higher heating value (HHV) to electricity has existed since the early 1980's. Suitable for oxidation in low-, intermittent-, or high-temperature configurations, ammonia fuel cells can be designed to meet specific performance (i.e. efficiency and capacity) requirements.

Further reading

- V. Agosta, "The Ammonia Economy", Mechanical Engineering Magazine, 2003.
- J. Ganley, "Intermediate Temperature Direct Ammonia Fuel Cells", Howard University, 2007
- A. T-Raissi, "Hydrogen from Ammonia and Ammonia-Borane Complex for Fuel Cell Applications" Proceedings of the 2002 U.S. DOE Hydrogen Program Review.
- M. B. Biradar, "Design, Scale-Up, and Integration of an Ammonia Electrolytic Cell with a Proton Exchange Membrane (PEM) Fuel Cell" Master of Science thesis. Ohio University, November 2007.
- P. Feibelman and R. Stumpf, "Comments on Potential Roles of Ammonia in a Hydrogen Economy – A Study of Issues Related to the Use of Ammonia for On-Board Vehicular Hydrogen Storage" Sandia National Laboratories, 2006.
- A. McFarlan "Development of Direct Ammonia Fuel Cells for Efficient Stationary CHP Applications" Natural Resources Canada, 2007.
- R. W. Henderson, "Ammonia Fuel Cells", JHU/APL FTT-044-81, 1981
- PCT Application WO 2007/047630 A2 "Carbon fiber-electrocatalysts for the oxidation of ammonia and ethanol in alkaline media and their application to hydrogen production, fuel cells, and purification systems".
- M. Cooper, G. Botte, "Hydrogen production from the Electro-oxidation of Ammonia Catalyzed by Platinum and Rhodium on Raney Nickel Substrate" Journal of The Electrochemical Society, 153 10 A1894-A1901, 2006.
- D. Teske. "Concerning the economic toll of America's oil dependence" National Farmers Union, 2007.
- R. Pitt, "Case study of fate and effects of ammonia spills", 2002.
- T. Saikia et al, "Study of hydrogen supply system with ammonia fuel", JSME International Journal Series B, Vol. 49, No. 1, 2006, pp.78-83 .
- JJ. MacKenzie, "Ammonia fuel: the key to hydrogen-based transportation," World Resources Inst., Washington, DC
- "Hazards of ammonia releases at ammonia refrigeration facilities" United States Environment Protection Agency.
- "Evaluation of the impact of the introduction of hydrogen as fuel to power motor vehicles considering the safety and environmental aspects" TRW Limited. 2007.
- "Potential roles of ammonia in a hydrogen economy", U. S. Department of Energy.
- V. Smil, "Enriching the earth", MIT Press.
- G. J. Leigh, "The world's greatest fix", Oxford University Press.
- N. A. Mignone, "Biological inhibition / Toxicity control in municipal anaerobic digestion facilities".
- J. Holbrook, "BioAmmonia - A zero-emissions fuel from biomass", AmmPower LLC, 2007
- "Nitrogen – Fixed", US Geological Society, 2007
- U. Bossel and B. Eliasson, "Energy and the Hydrogen Economy", 2003

About Elucidare Limited

Founded by Dr David Nugent in 2003, Elucidare Limited provides technical, commercial and strategic due diligence services to the financiers of early-stage technology companies. Key sectors include optoelectronics, semiconductors, medical imaging, wireless communications, homeland security, and renewable technologies. Our clients include many of the largest Venture Capital, Private Equity and Institutional Investors in Europe. In addition we assist the commercialisation of intellectual property arising from European universities, either in the form of licensing agreements or full commercial spin outs. Elucidare is not regulated by the Financial Services Authority and thus does not provide any services pertaining to investment advice.

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