NH_3 – The Optimal Alternative Fuel

ARPA-E REFUEL Kickoff Meeting

August 17-18, 2017

Denver, Colorado

Norm Olson
President - NH3 Fuel Association

NH_3 – Optimal Fuel, Versatile Chemical

Fuel

Fertilizer

Energy Storage

Refrigerant

NH3 FA and AIChE Meeting

Become a member of the NH3 FA and attend the AIChE Annual Meeting at a significant discount (see details at link below).

https://nh3fuelassociation.org/join-us/

AIChE 2017 Annual Meeting. October 29-November 3. Minneapolis, MN

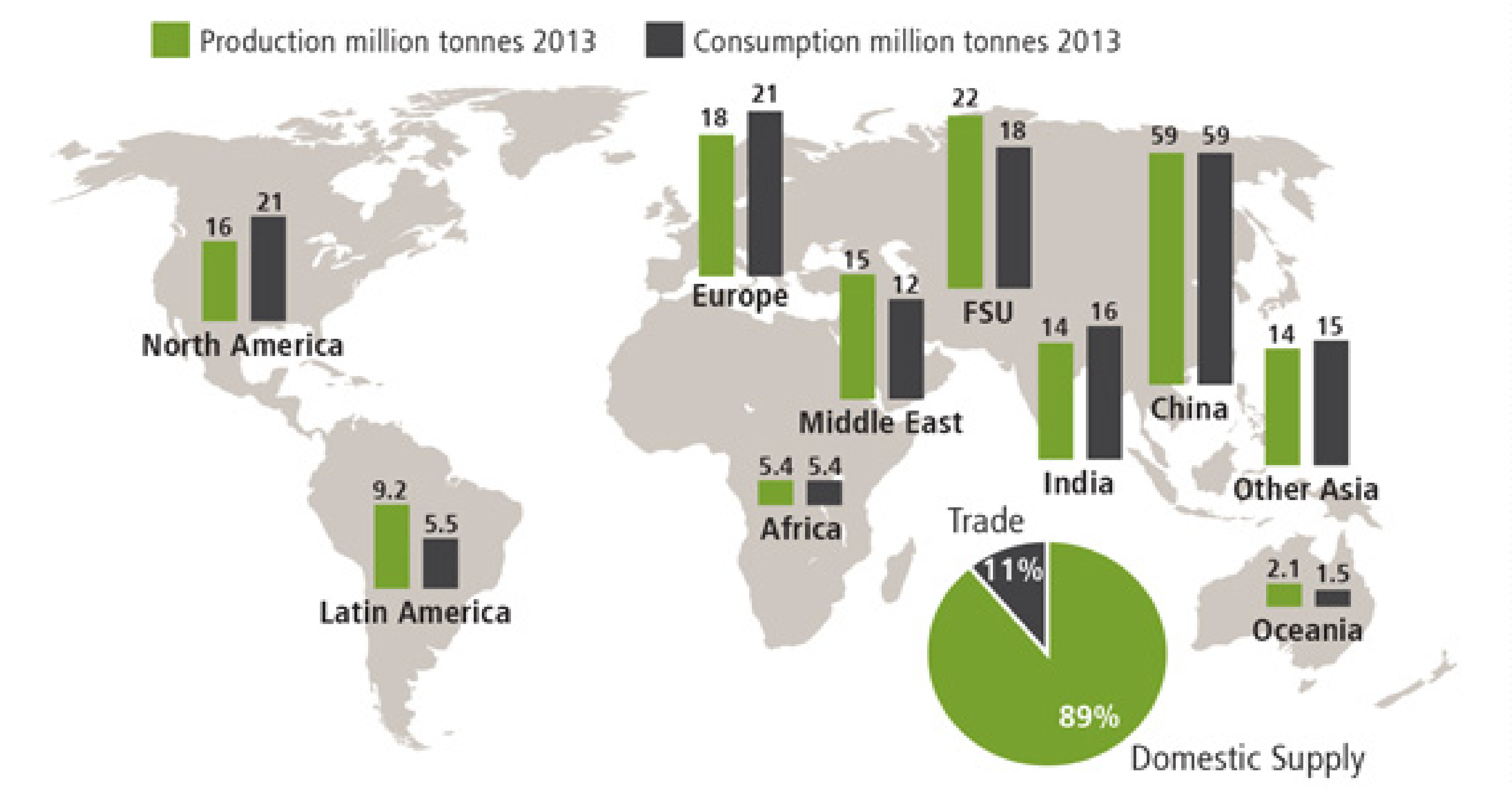
NH3 Energy+ Topical Conference. 40 presentations!

Recent Developments

Netherlands Conference (~150 attendees) - Europe's First! Shell, Yara, Ammonia Casale, IEA, Siemans, Proton Ventures, etc. 2017

Japan Program 2015-2018
Siemens wind to NH_3 project in Great Britain 2016-2017 (UMM 2008)
Global NH_3 Fuel Federation 2016
IEA – white paper 2017
Ammonia Casale – 10 tpd unit announced 2017
Australia – 1st non-U.S. NH_3 FA chapter 2017
ARPA-E DOE – 13 NH_3 fuel related projects 2017
AIChE – 40 presentations 2017
ACS – first ever NH_3 fuel session in 2017
Hydrofuel - Greg Vezina, 1981
And many more

NH3 Facts - Production

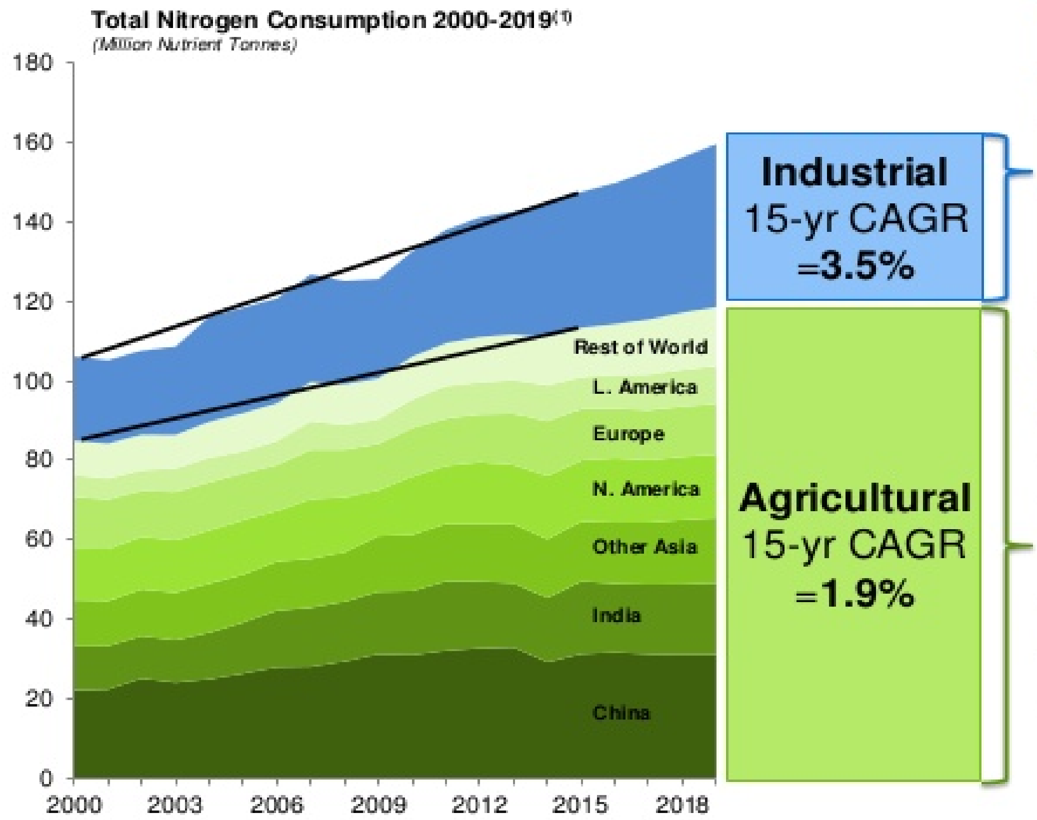


Source: Fertecon, CRU, PotashCorp. Last updated: Aug 31, 2014

NH3 Facts - Consumption

CF Expects Global Nitrogen Demand To Grow at 2 Percent per Year

CFIndustries



Product	Percentage of 2015 Demand
IGAN: Explosives	16%
Urea: resins, amines	33%
Ammonia: Caprolactam, Acronitrile, Polymers	51%

Product	Percentage of 2015 Demand
D.A. Ammonia	3%
AS	5%
UAN	6%
AGAN	8%
CAN/ Compounds	21%
Urea	57%

(1) Actual values from 2000-2015; projections from 2016-2019

Data Sources: Fertecon, IFA, AAPFCO, Fertilizer's Europe, ANDA
Analysis: CF Industries

NH3 Production vs U.S. Gasoline Use

U.S. Gasoline Consumption: 143 Billion Gallon (2015)

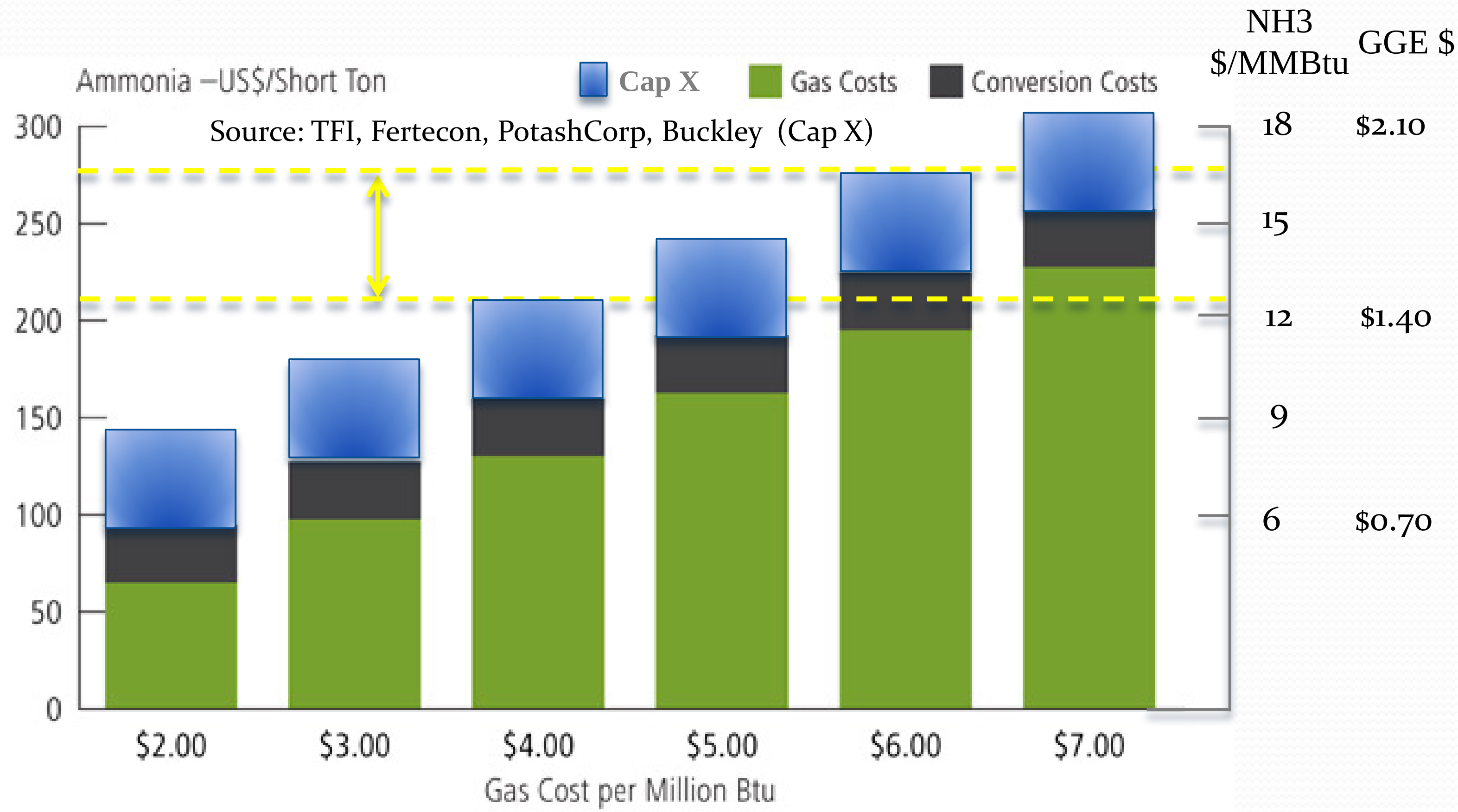
2016 World NH3 Production: 180 million tonne = ~80 Billion Gallon = ~40 Billion GGE

~3.5x

NH_3 Affordability

Similar to propane infrastructure costs
2nd most transported chemical in world
Over 3000 miles of NH3 pipeline in U.S.
800 retail outlets in Iowa alone
1.3 times more hydrogen than liquid H2 (by volume)

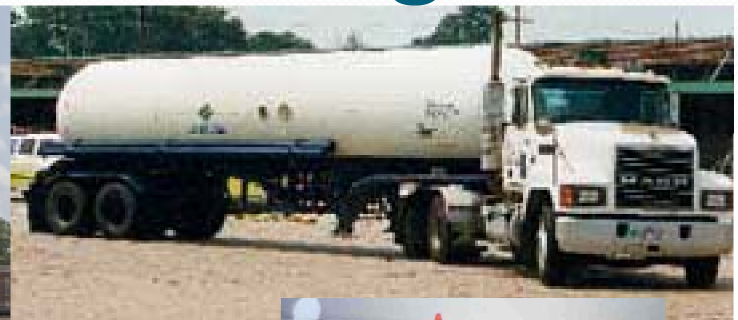
NH_3 Production Costs w/ Cap X



Natural Gas Represents More Than 75 Percent of US Producers' Costs
Natural gas is the most important feedstock in ammonia production and, depending on price, makes up 70-85 percent of the US cash cost of producing ammonia. Cap X: $1500/ton, 30 year amortization, ~$50/ton

Gasoline @ $3.50/gallon = $30/MMBtu

Ammonia Storage & Transport



1st Hydrogen Shipment? Not really.

"Australia and Japan prepare for world's first bulk hydrogen shipment "
Zoe Reynolds | 11 January 2017

NH3 vs Hydrogen Storage Costs

	NH3 (250 psi)	CNG (3200 psi)	H2 (10k psi)	Cryo NH3 (-28 F)	Cryo H2 (-423 F)
Application					
On-board vehicle [1]	\$700	\$1500	\$6000		
Filling station	\$68,000[2]		\$2,643840[3]		
Large storage facility				\$20 million[4]	\$81.6 million[3]

[1]Phone conversation with John Coursen, Worthington Industries, February 17, 2017. Relative ~costs ~50 liter tank: LPG/NH3 - \$700, CNG (3200 psi) - \$1500, Hydrogen (10,000 psi) - \$6000.

[2]1Phone conversation with Don Wallace, Trinity Containers. 18,000 gallon NH3 bullet tank - \$68,000. @80% fill capacity = 14,400 gallon x 5lbs/gallon x 0.176 lbs H2/lb NH3 /2.2 lbs/kg = 5760 kg = \$11.81/kg H2.

[3]"Hybrid Hydrogen Energy Storage", Michael Penev, May 22, 2013. 10k psi H2: \$459/kg x 5760 kg = \$2,643,840. Cryo H2 Storage: \$25.5/kg x 3.2 million kg= \$81.6 million.

[4]Rentech Press Release, January 12, 2012. Chilled NH3 20,000 ton = \$20 million. 20k ton x 2000 x 0.176 /2.2 lbs/kg = 3.2 million kg. H2.

What Makes NH_3 Optimal?

- Affordability
- **Safety**
- Efficiency
- Environmental Performance
- Sustainability
- Production Flexibility
- End-Use Flexibility
- County Building

Safety

Numerous design choices – As safe as it needs to be.

Pressurized storage – safe enough to meet most stringent standards
Chilled storage – safer yet: -28 F NH_3, -265F LNG, -420F H_2
Chemical storage – Too safe? Amminex, ammonium carbonate (solids)

Ammonia's Safety Reputation: Whence comest thou?

Bhopal, 1984, Union Carbide, Methylisocyanate release, 1000's killed.

U.S. response:- EPCRA developed, 300 "extremely hazardous chemicals".
NFPA: 2 to 3 arbitrarily.

40 times more lethal. EV range 100 x 40 = 4000 miles
40 mpg x 40 = 1600 mpg

Safety LC50

	Table 1: Toxicity Classes: Hodge and Sterner Scale (CCOHS)					
			Routes of Administration			
			Oral LD50	Inhalation LC50	Dermal LD50	
Corresponding NFPA Ratings (LC50)	Toxicity Rating	Commonly Used Term	(Single dose to rats) mg/kg	(Exposure of rats for 4 hours) ppm	(Single application to skin of rabbits) mg/kg	Probable Lethal Dose for Man
	1	Extremely Toxic	1 or less	10 or less	5 or less	1 grain (a taste, a drop)
4 (0-100)	2	Highly Toxic	1-50	10-100	5-43	4 ml (1 tsp)
3 (100-500)	3	Moderately Toxic	50-500	100-1000	44-340	30 ml (1 fl. oz.)
2 (500-2500)	4	Slightly Toxic	500-5000	1000-10,000	350-2810	600 ml (1 pint)
1 (2500-20,000)	5	Practically Non-toxic	5000-15,000	10,000-100,000	2820-22,590	1 litre (or 1 quart)
0 (>20,000)	6	Relatively Harmless	15,000 or more	100,000	22,600 or more	1 litre (or 1 quart)

Source: Canadian Centre for Occupational Health and Safety (CCOHS). NFPA data addition by Norm Olson, NH3 FA**.**

LC50/4hour (ppm): NH3 - 2000; Chlorine – 146.5; Methyl Isocyanate – 5 (**Source**: Praxair, other)

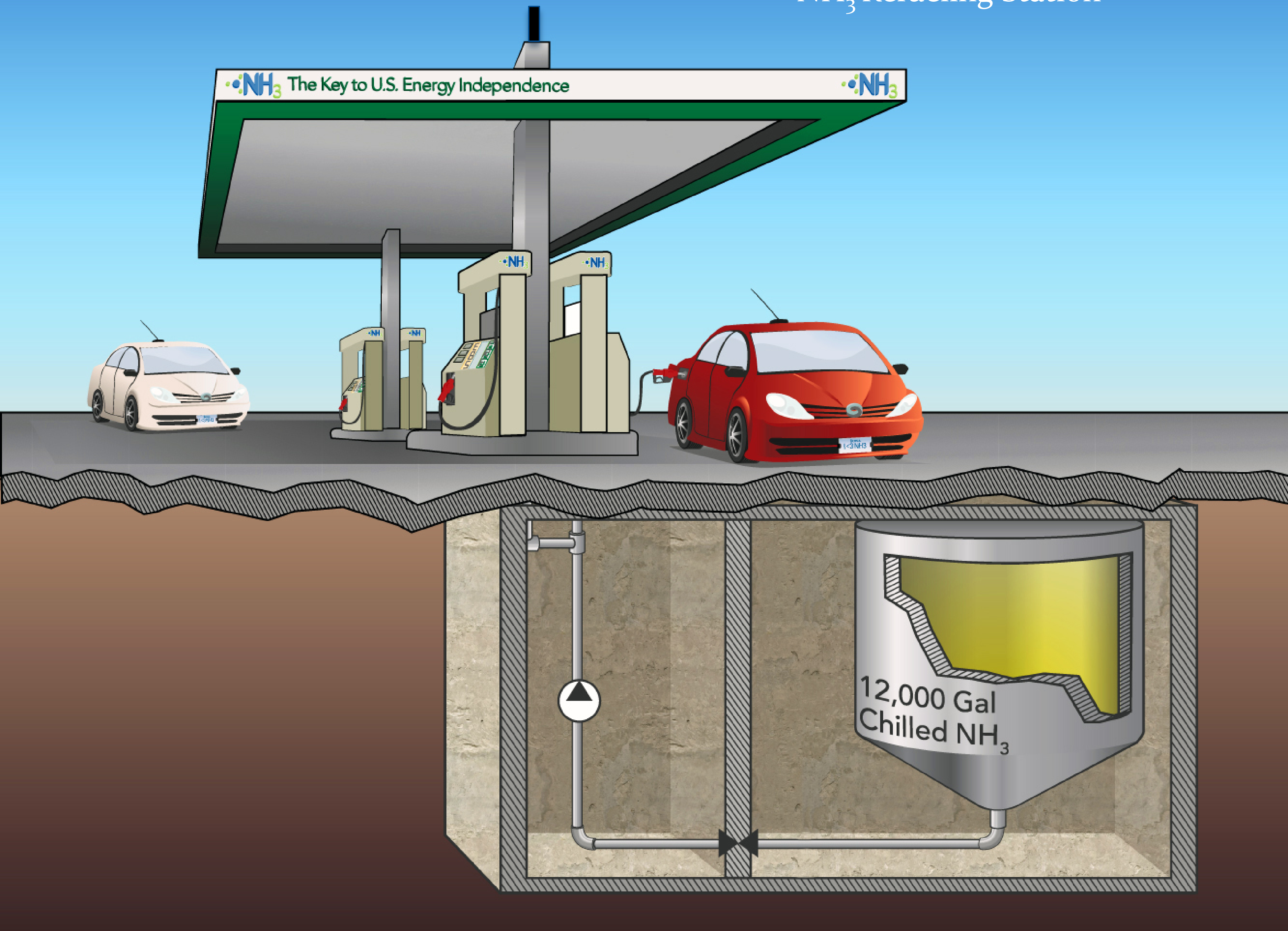
Safety I

- **NH3 is a common, naturally occurring chemical found in or used by nearly all animal life forms. It is not a carcinogen and is not a greenhouse gas. Its ozone depletion number is zero.**
- **NH3 is safer than propane and as safe as gasoline when used as a transportation fuel.**
- **The Iowa Energy Center funded a comparative quantitative risk assessment (CQRA) study completed March 2009, by Quest Consultants Inc., Norman, Oklahoma. "Comparative Quantitative Risk Analysis of Motor Gasoline, LPG, and Anhydrous Ammonia as an Automotive Fuel", June, 2009.**
- **"Safety assessment of NH3 as a transportation fuel", Nijs Jan Duijm, Frank Markert, Jette Lundtang Paulsen, Riso National Laboratory, Denmark, February, 2005**

Safety II

- **NH3 plant operators – hydrogen vs NH3**
- **NH3 is classified by DOT as a non-flammable liquid and an inhalation hazard (not a poison)**
- **The degree of safety for NH3 Fuel is an *engineering decision* and does not require any technology miracles/breakthroughs (unlike hydrogen and electric vehicles).**
- **The challenge: Design an ASME tank and valve system that is fail safe. A rather trivial challenge.**

NH_3 Refueling Station



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Production Energy Efficiency

	kWh/kg H2	%LHV
NH3 via Haber-Bosch	2.26[1]	6.8%
700 bar H2 Refueling (880 bar)	2.85[2]	8.5%
Liquid H2	10[2]	30.1%
Liquid H2 (advanced)	7[2]	21.1%

[1] "Efficient Ammonia Production" Power Point presentation, page 63. Jim Gosnell, KBR. 2005 NH3 Fuel Association Meeting. Argonne National Laboratory.

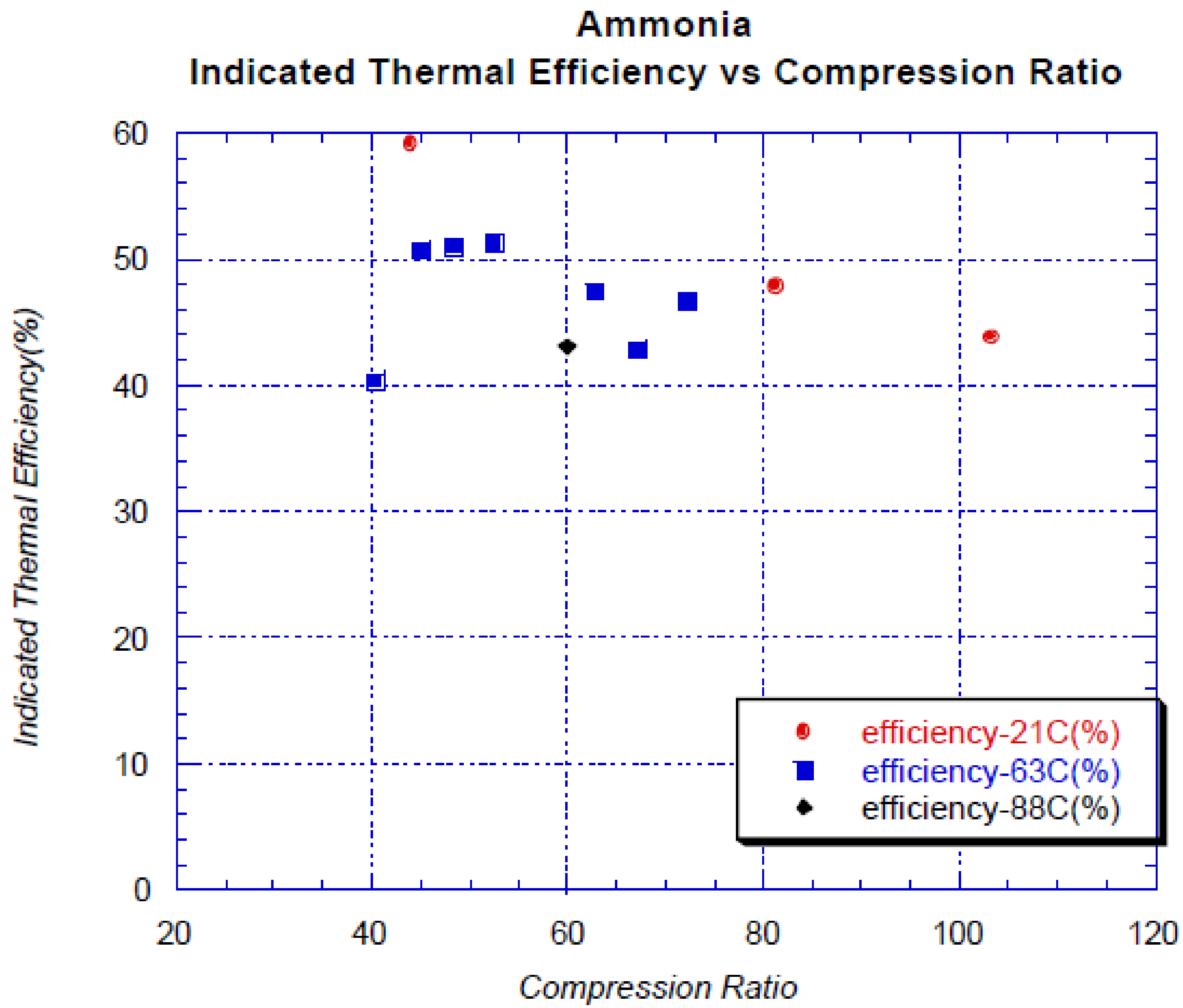
[2]Source H2 Data: "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs." DOE Hydrogen and Fuel Cells Program Record. Record #: 9013. July 7, 2009. Air Products and Chemicals Inc. (APCI). 2.67 + 0.18 = 2.85. Page 3 of resource above.

Efficiency in Engines

Octane, Octane, Octane

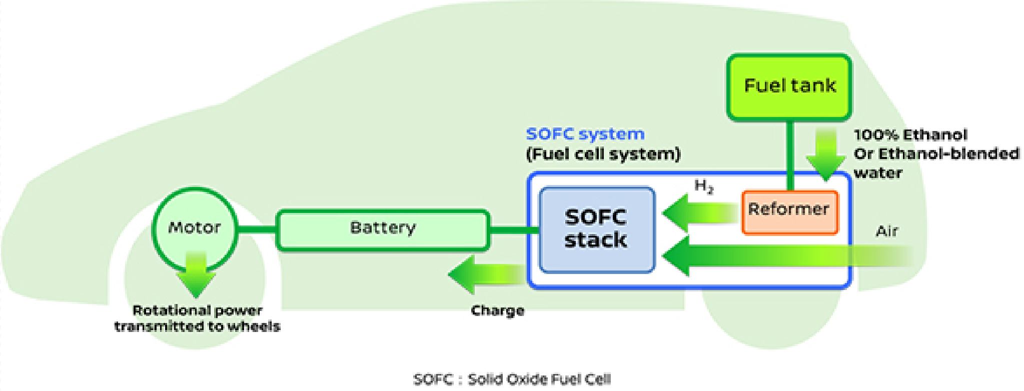
NH_3's very high octane rating (>120) and high (tunable) resistance to detonation allow the use of extremely high compression ratios and therefore IC engines with the highest possible efficiencies.

NH_3 IC Engine Efficiency



Source: Van Blarigan, Sandia National Lab, 2001

Nissan SOFC Vehicle – 60% Eff. ?



https://www.youtube.com/watch?v=HF-eE8pRzMw

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Cleaner Than Hydrogen?!

No carbon
NH_3 used to clean up NO_x
Zero measurable pollutants possible with IC engines
Not a greenhouse gas
Ozone depletion number of zero
Not a known carcinogen
Huge natural occurrence in the earth's nitrogen cycle
Natural mechanisms for spill remediation

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Sustainability

As long as the sun continues to shine, the earth' s atmosphere contains significant amounts of nitrogen, there is some readily available source of hydrogen, and iron is available as a catalyst….

NH3 will be sustainable on planet earth!

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- End-Use Flexibility
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Production Flexibility

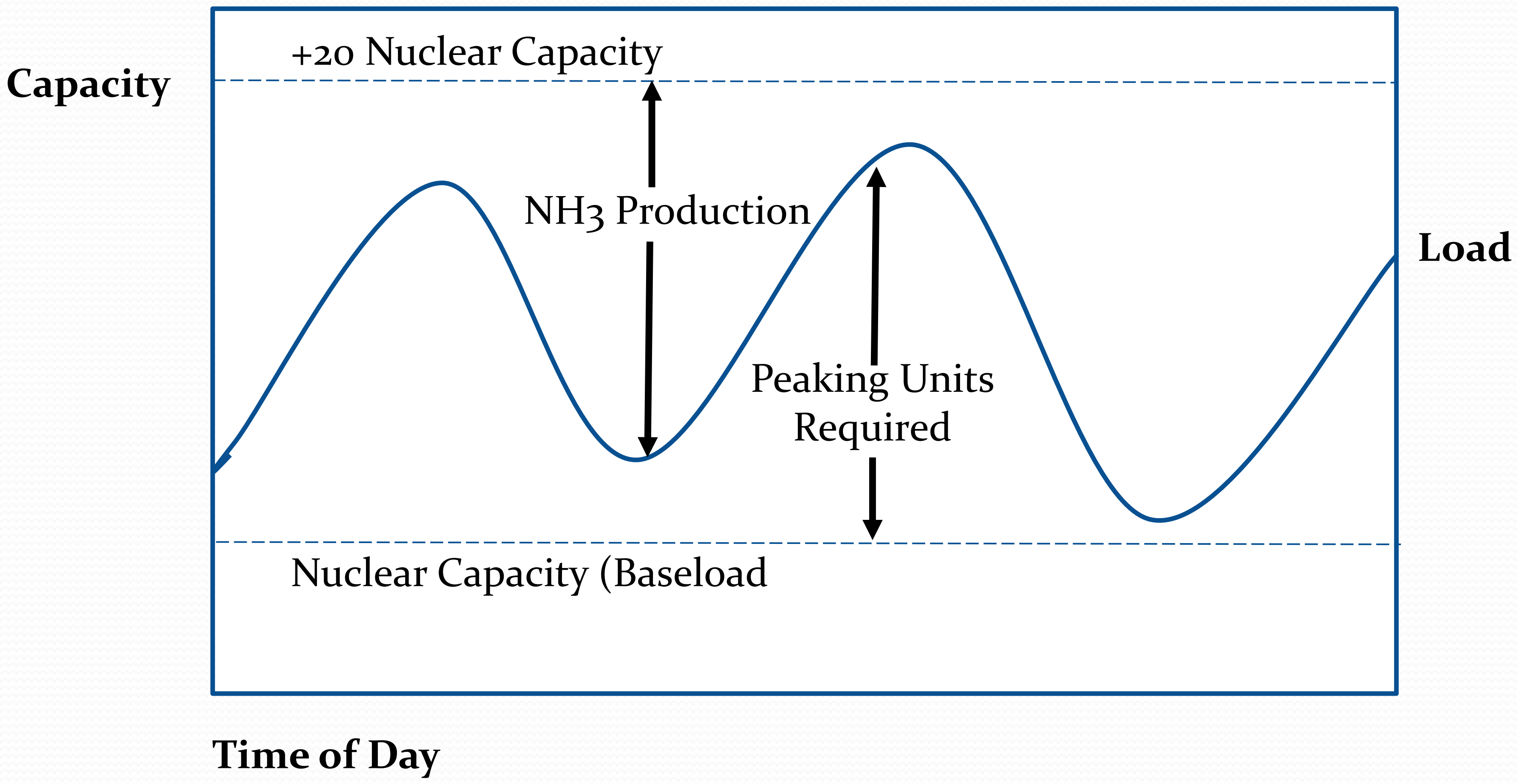
NH_3 can be produced using any and all primary energy sources including but not limited to …. Solar, natural gas, wind, nuclear, OTEC, coal, hydro, etc.

Scalability of NH_3 production plants is very good and could range from units as small as one ton per year to mega-ton production facilities.

Affordable NH_3 could be produced from (carbon free) natural gas now and from any renewable energy source (and water) in the near future.

Several promising new alternative NH_3 production technology alternatives are being developed (i.e. alternatives to Haber-Bosch)

Nuclear Synergism – Fusion?



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End Use Flexibility

SI engines
CI engines – dual fuel now…high compression future
Fuels cells
Gas turbines
Burners

Optimizing prime movers for a single fuel has huge benefits. An engine designed to use both gasoline and ethanol severely compromises the efficiency potential of ethanol, another very-high octane fuel.

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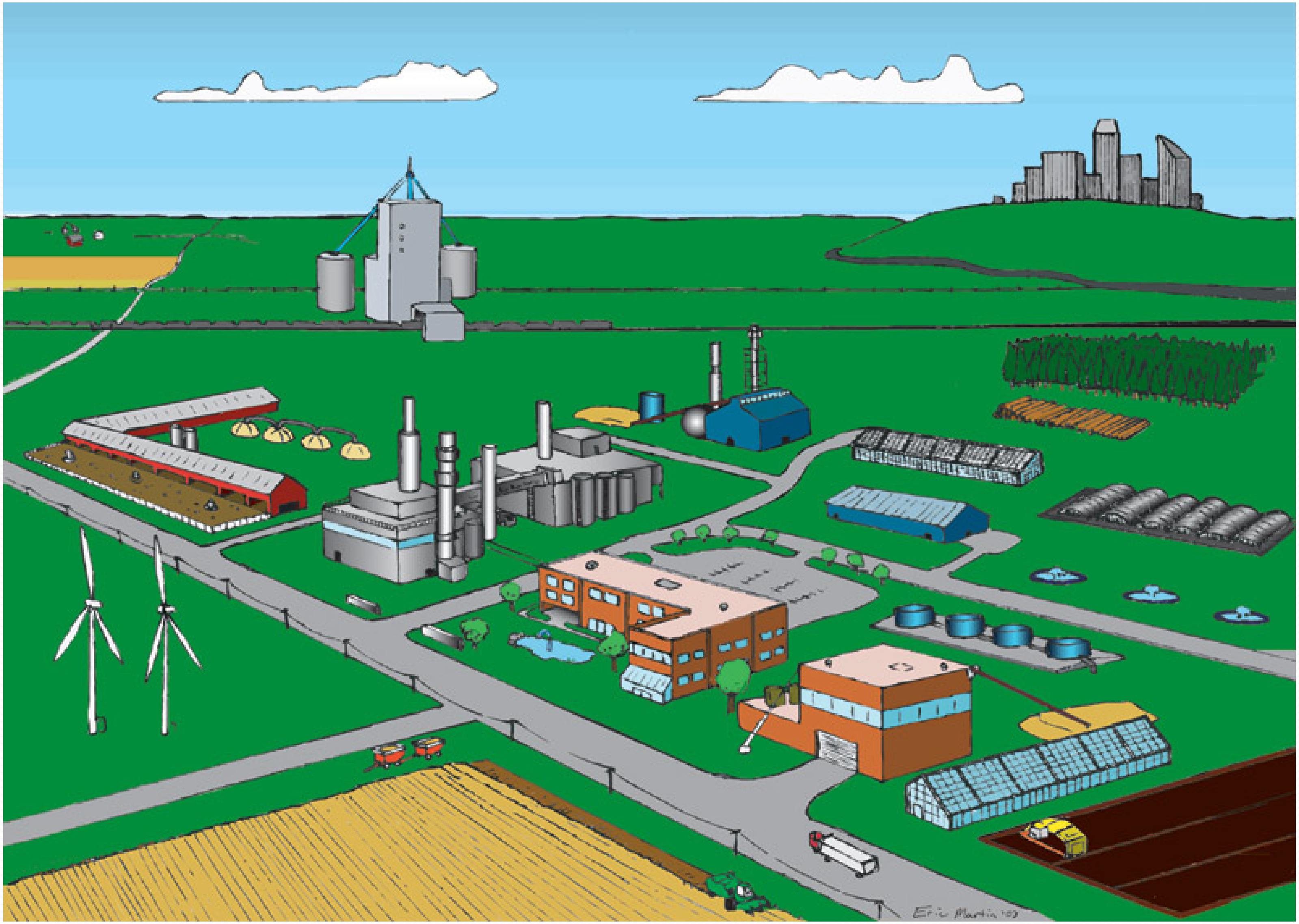
Sustainable, Self-Sufficient Community

NH_3 fertilizer made from a fraction of the net increase in crop residue (e.g. corn stalks) due to the addition of NH_3 fertilizer , allows a transition from subsistence farming to income-producing farming.
NH_3 fuel allows for locally produced transportation fuels and rural combined heat & power (CHP) units.
NH_3 refrigerant allows for efficient and environmentally-friendly cold food and perishables storage.

Where another of our other favorite chemicals (H_2O) exists, one relatively simple refinery producing NH_3 can provide enhanced, sustainable food production; a versatile transportation fuel; distributed electrification via CHP units; long-term, efficient renewable energy storage; and efficient refrigeration systems. This provides an excellent base for local self-sufficiency and a greatly improved standard of living.

Petroleum refineries are very complex and require a very large scale.

Bio-Refinery

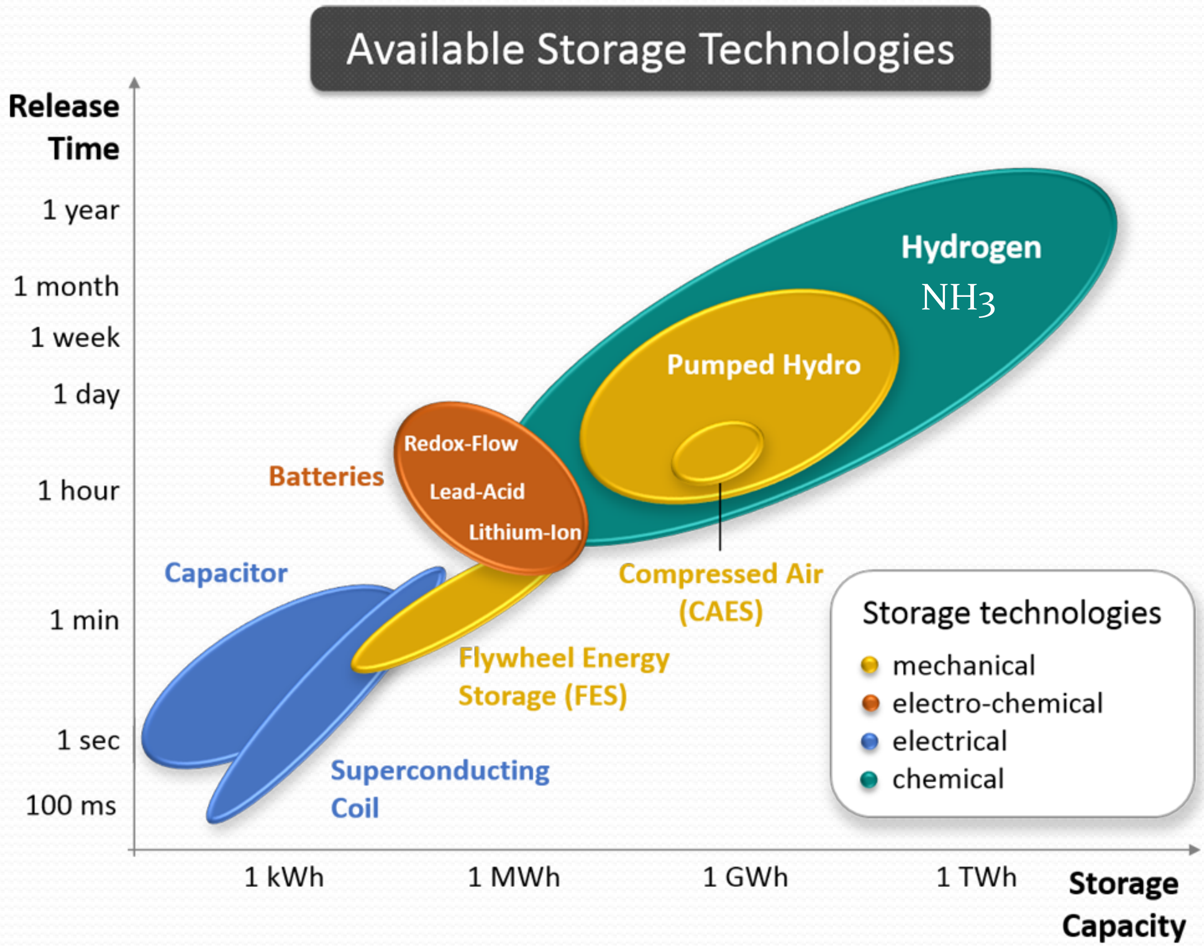


Renewable Energy: Stranded and Long-term Storage

A significant amount of renewable energy will either be stranded (i.e. produced remotely and converted to a form that can be transported long distances) or will need long-term storage. Chemical storage likely be used for these two applications. NH_3 will likely be the most cost-effective option for chemical storage.

Once renewable energy is stored as NH_3, it is more efficient and cost-effective to use the NH_3 as a liquid transportation fuel in FCV and/or ICEV than to convert it to electricity and deliver it through the grid to EV filling stations for use in EV's.

Effective Energy Storage



Source: Hydrogenius Technologies. NH3 addition by NKO.

NH3 vs H2 vs Methylcyclohexane

700 bar Hydrogen - 0.03899 g/cm3 x 100% H_2 = 0.03899
Liquid Hydrogen (-253 C)– 0.07099 g/cm3 x 100% H_2 = 0.07099
Liquid Ammonia (NH_3, -33C) – 0.682 g/cm3 x 17.6% H_2 = 0.12003
Methylcyclohexane (MCH) – 0.77 g/cm3 x 6.1% H_2 = 0.04700

NH_3 dehydrogenation requires 31 kJ/mol H_2. Methylcyclohexane dehydrogenation requires 68 kJ/mol H_2, or ~ 2.2 times more energy per mole of hydrogen than for NH_3.

	kWh/kg H2	%LHV
NH3 via Haber-Bosch	2.26[1]	6.8%
700 bar H2 Refueling (880 bar)	2.85[2]	8.5%
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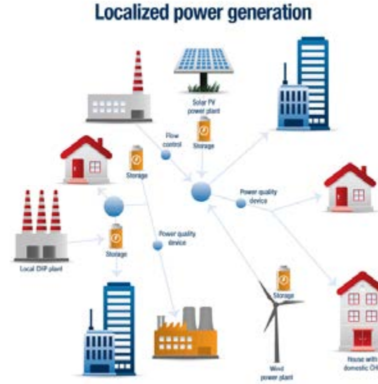
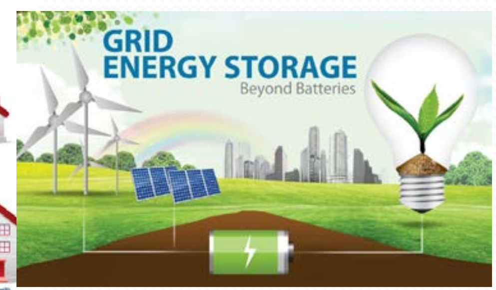
NH_3 Big Picture

NH3 NH3 NH3 NH3 NH3 NH3 NH3 NH3

Transportation

Agriculture





Conclusion

NH_3:

is clearly, the most affordable carbon-free fuel
is the most efficient fuel in an internal combustion engine
has optimal environmental performance
has production flexibility second to none
has excellent end-use flexibility (tunable fuel)
has tremendous business development opportunities
is the optimal choice for an alternative fuel

Many times "all of the above" or diversity is very beneficial – primary energy source diversity, food diversity, locations to live, music

Some times selecting one, optimal choice (standardization) has huge benefits – meanings of words, standard weights and measures, transportation/generation fuels.

Optimized engine/fuel cell/turbine cost/efficiency/emissions; optimized, non-redundant infrastructure; safety protocol optimization; optimized production effectiveness…

Prodigious business opportunity and tremendous world-wide benefits.

Top Technology Developments

Vaccines

Synthetic Ammonia Fertilizer (Haber-Bosch)

Personal Computer

Internet

NH_3 Energy?

NH_3 – The Optimal Alternative Fuel

Thank You!

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https://nh3fuelassociation.org/