THE LEADER IN ON SITE GAS GENERATION.

Green Ammonia and H2@Scale: An Industry Perspective

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Presentation Outline:

- Introduction: the RH2 pathway to green ammonia
- Ammonia today: energy, environment, markets, and scale
- H2@Scale: the ammonia energy play
- Research Needs: production pathways and applications
- Key Takeaways

Renewable ammonia production yesterday…

Rjukan, Norway; 1927 – 1970's

Glomfjord, Norway; 1953 – 1991

- Two largest electrolyser plants worldwide
- Capacity: 30 000 Nm^3/h each
- Energy consumption: approximately 135 MW each
- Supplied by renewable hydro power

…and new large industrial electrolyzer plants…

Company:	Nitol Solar
Industry:	Polysilicon
Start-up:	2011
Capacity:	1 940 Nm^3/h
Energy:	8,8 MW
Source:	Hydro Power

Company:	Tokuyama
Industry:	Polysilicon
Start-up:	2012 & 2013
Capacity:	2 500 Nm^3/h + 3 000 Nm^3/h
Energy:	Total 25 MW
Source:	Hydro Power

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Source: NEL Hydrogen

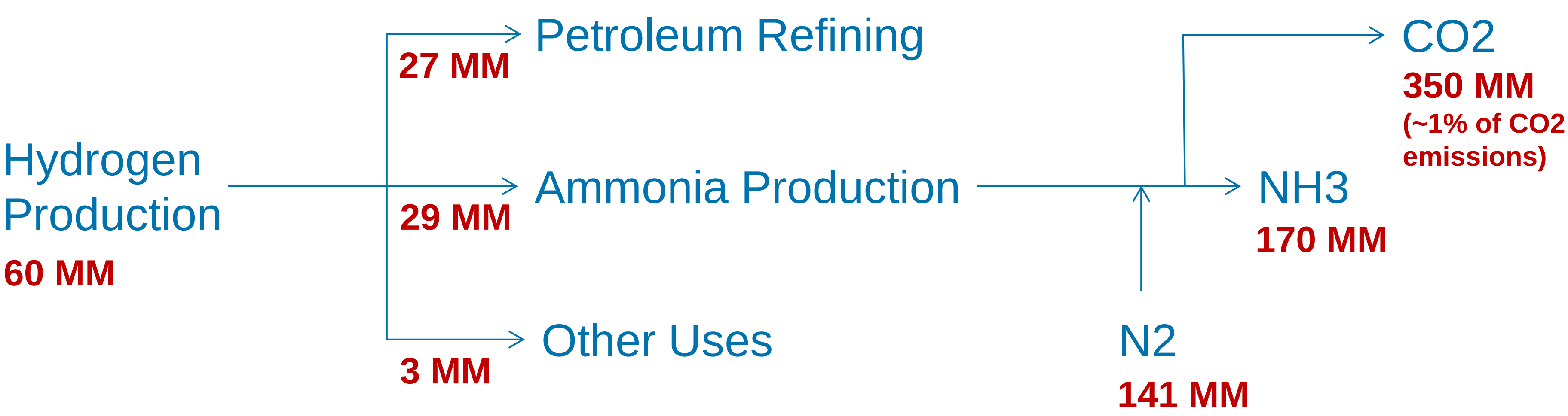
…and new pioneers on the NH3 energy frontier

Mike Reese at the Wind to Ammonia Pilot Plant dedication, left,
Jay Schmuecker's hydrogen/ammonia fueled tractor at ANL, right

Ammonia Today Is H2- and GHG-Intensive

Global H2/NH3 Mass Balance (Approximate)

Metric Tonnes, 2017

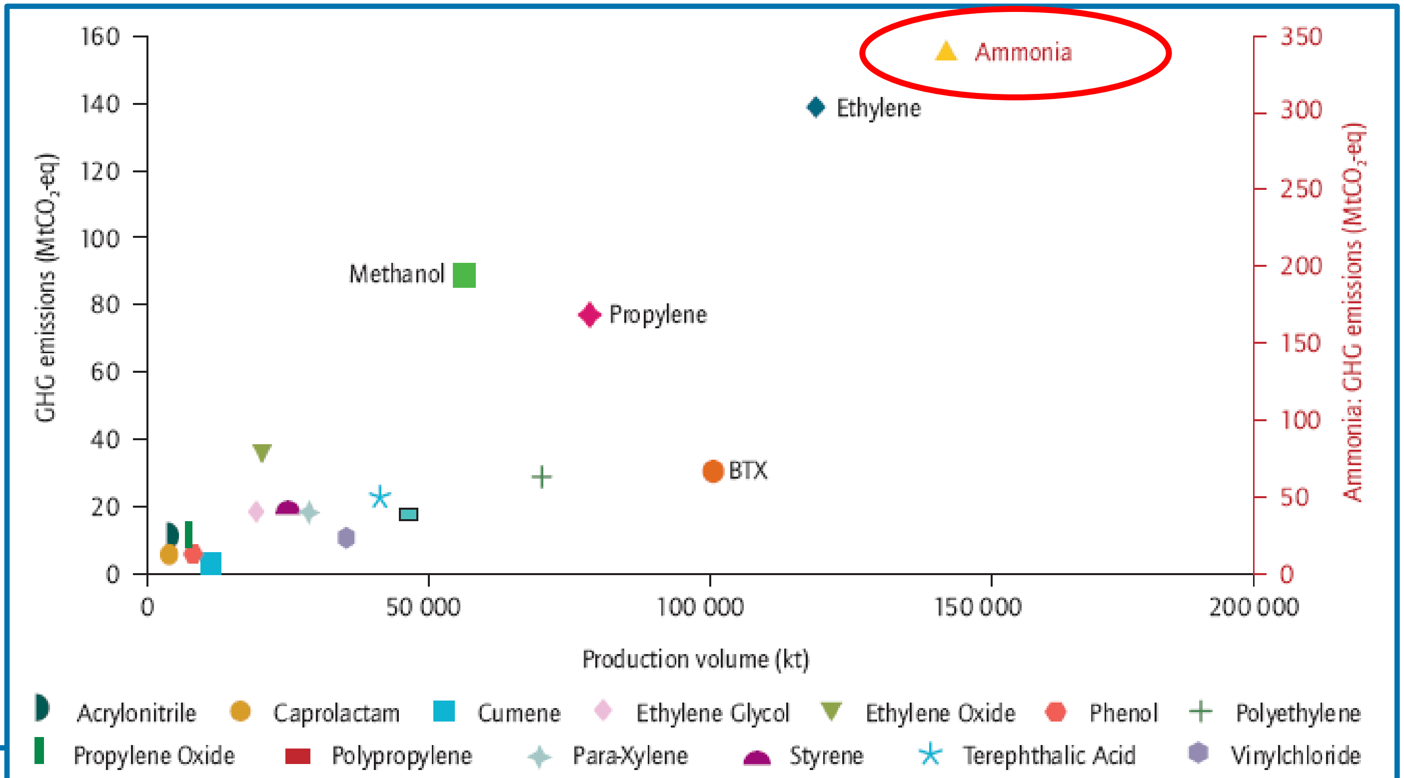


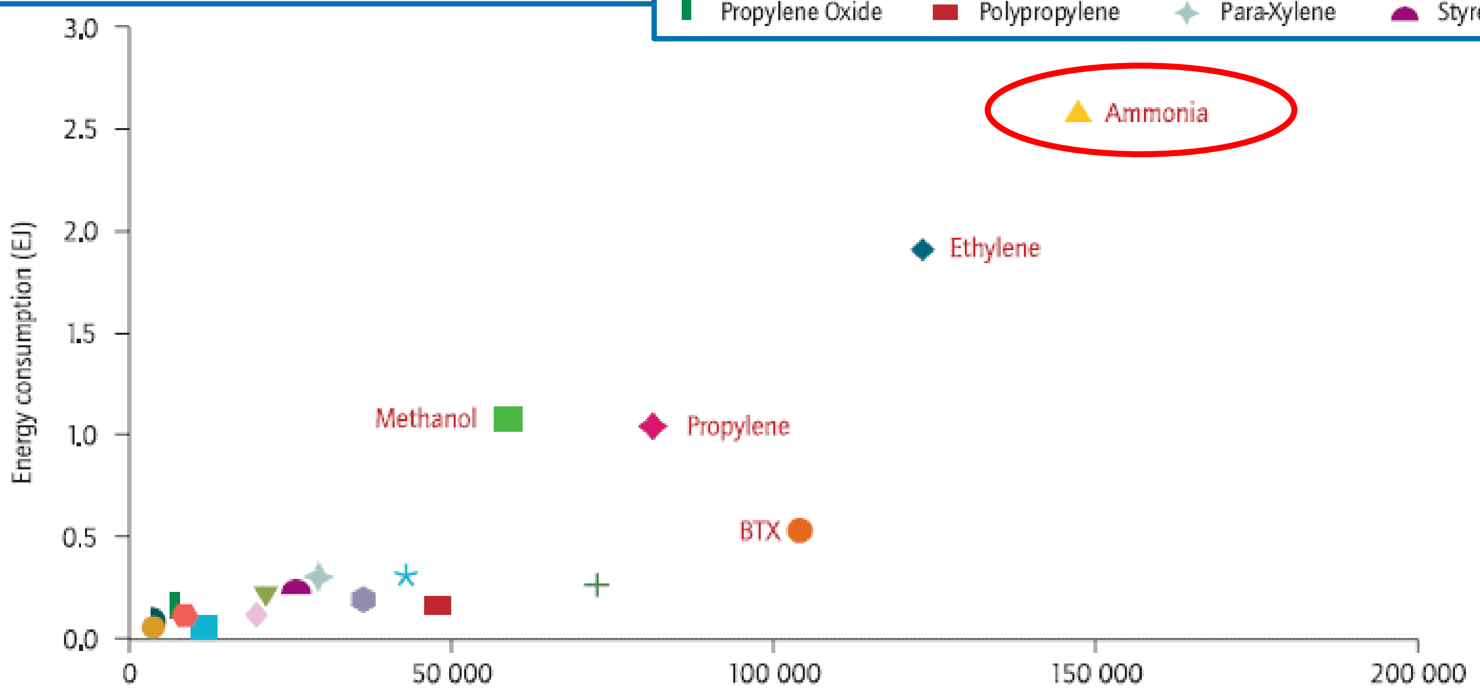
NH3 is a major consumer of fossil energy (coal and natural gas). In the U.S., it accounts for about 4% of industrial NG consumption.

Sources: 1. Mass balance: analysis based on figures from International Energy Agency. 2. Text box: analysis based on Lawrence Livermore National Lab depiction of U.S. energy flows in H2@Scale HTAC presentation, 4/6/16.

NH_3 Impact

Ammonia is #1 of 18 large volume chemicals for both energy use and GHG emissions, **largely due to the H_2 reformation step from SMR**

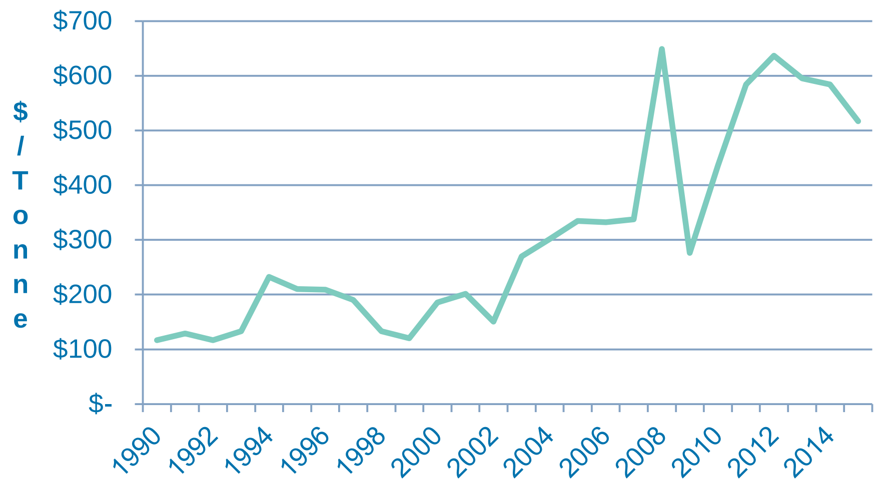




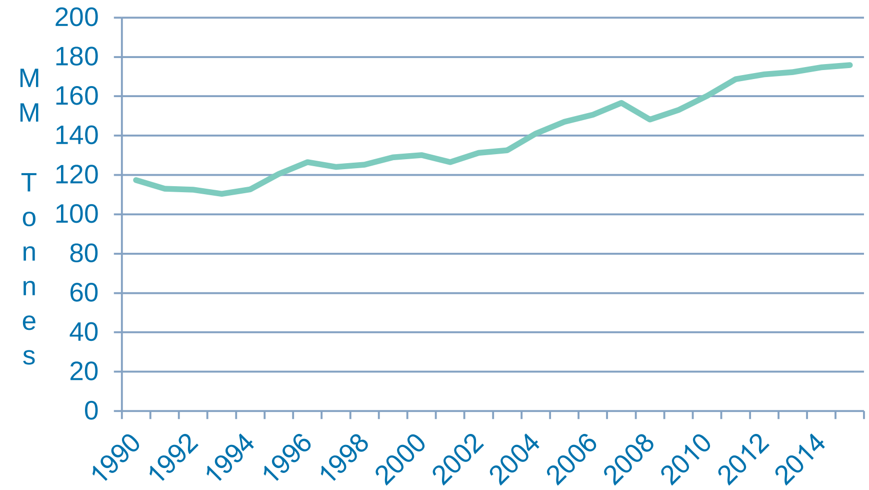
Reference:
Technology Roadmap Energy and
GHG reductions in the chemical industry via catalytic processes,
The International Energy Agency, 2013.

Ammonia Market Size and Growth

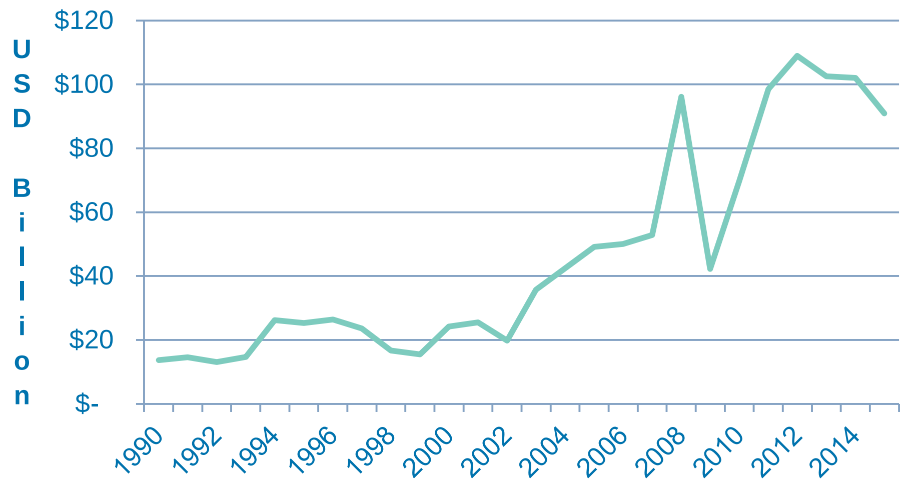
Price of Ammonia, F.O.B. U.S. Gulf Coast



Global Ammonia Production



Apparent Size of Global Ammonia Market



Growth Rates

CAGR Global Production 1990-2015: 1.6%

CAGR $ Market Size 1990-2015: 7.9%

Projected CAGR Global Production 2016-2050: 1.3%

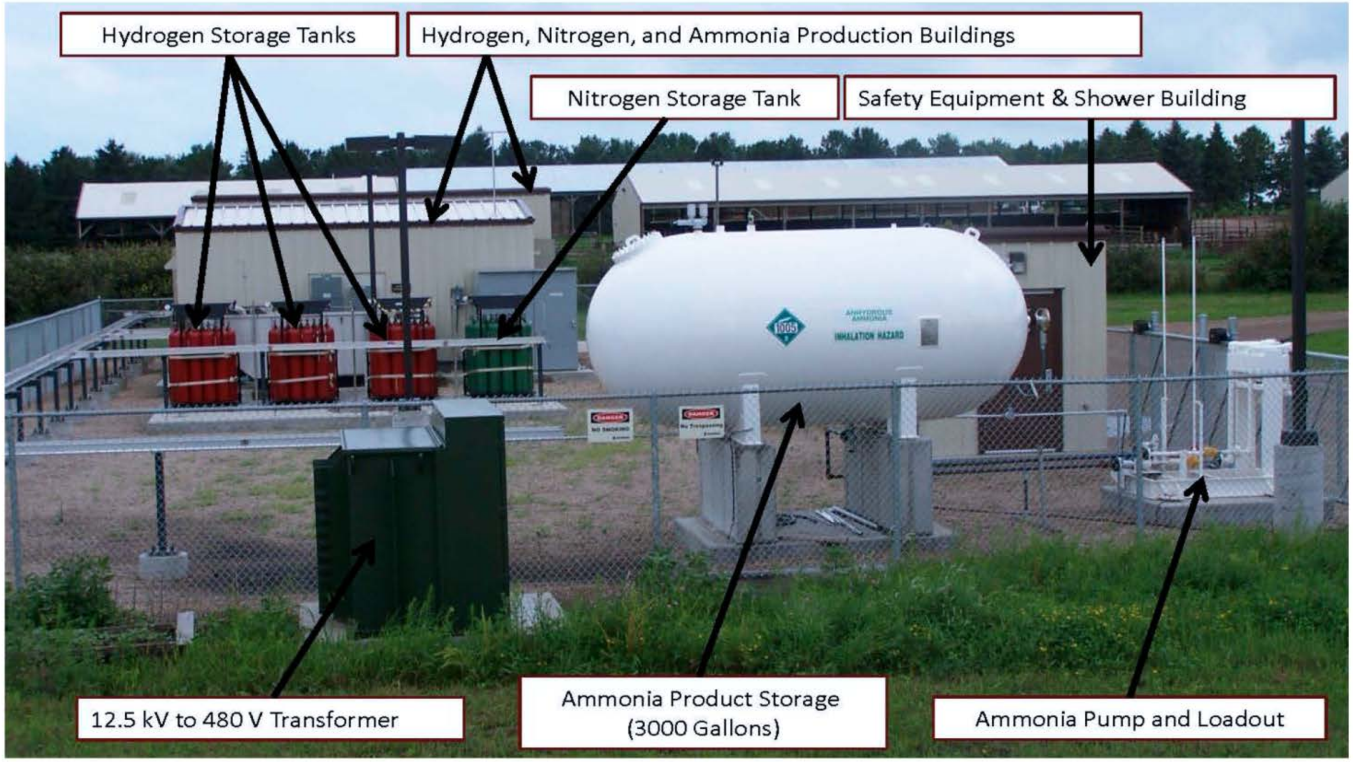
Source: "Nitrogen Statistics and Information", U.S, Geological Survey,11/16; International Energy Agency

For H2@Scale, distributed ammonia production needs to be a significant application for RH2

- **Distributed ammonia plants need to be scaled to available renewable energy resources.**
- **Example: UMinn's Zero-Emission Ammonia Pilot Plant, powered by an on-site wind turbine**

Morris, MN Ammonia Pilot Plant

Scaled down conventional Haber-Bosch process, 25 ton/yr capacity



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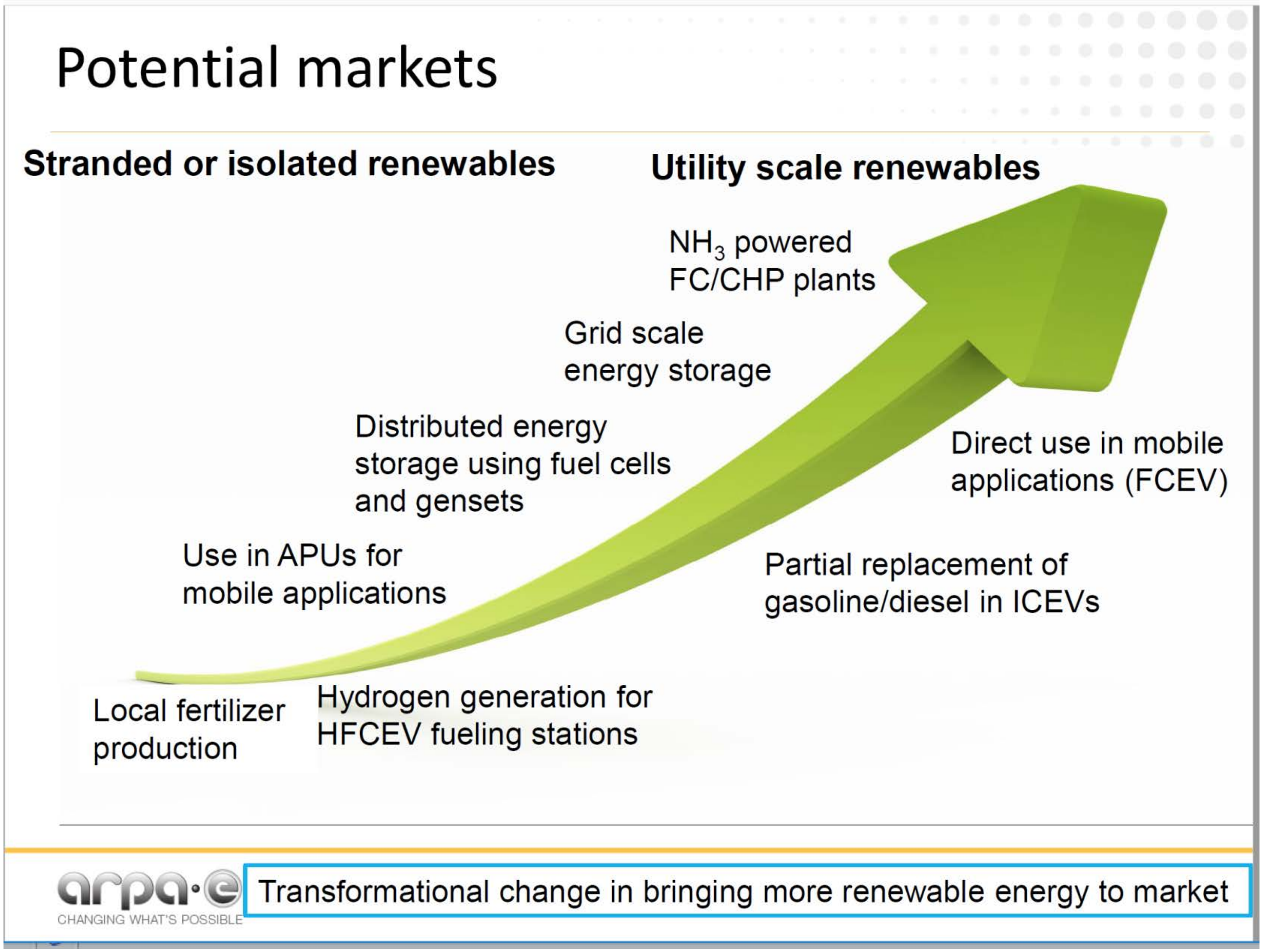
Sustainable Fertilizer Is Just the Beginning

- Systems analysis suggests that NH3 could be the most affordable way to transport H2 from site of production to site of use
- Think "H2 vector" rather than just fertilizer or industrial commodity



Source: Soloveichik, NH3 Fuel Conference 2016.

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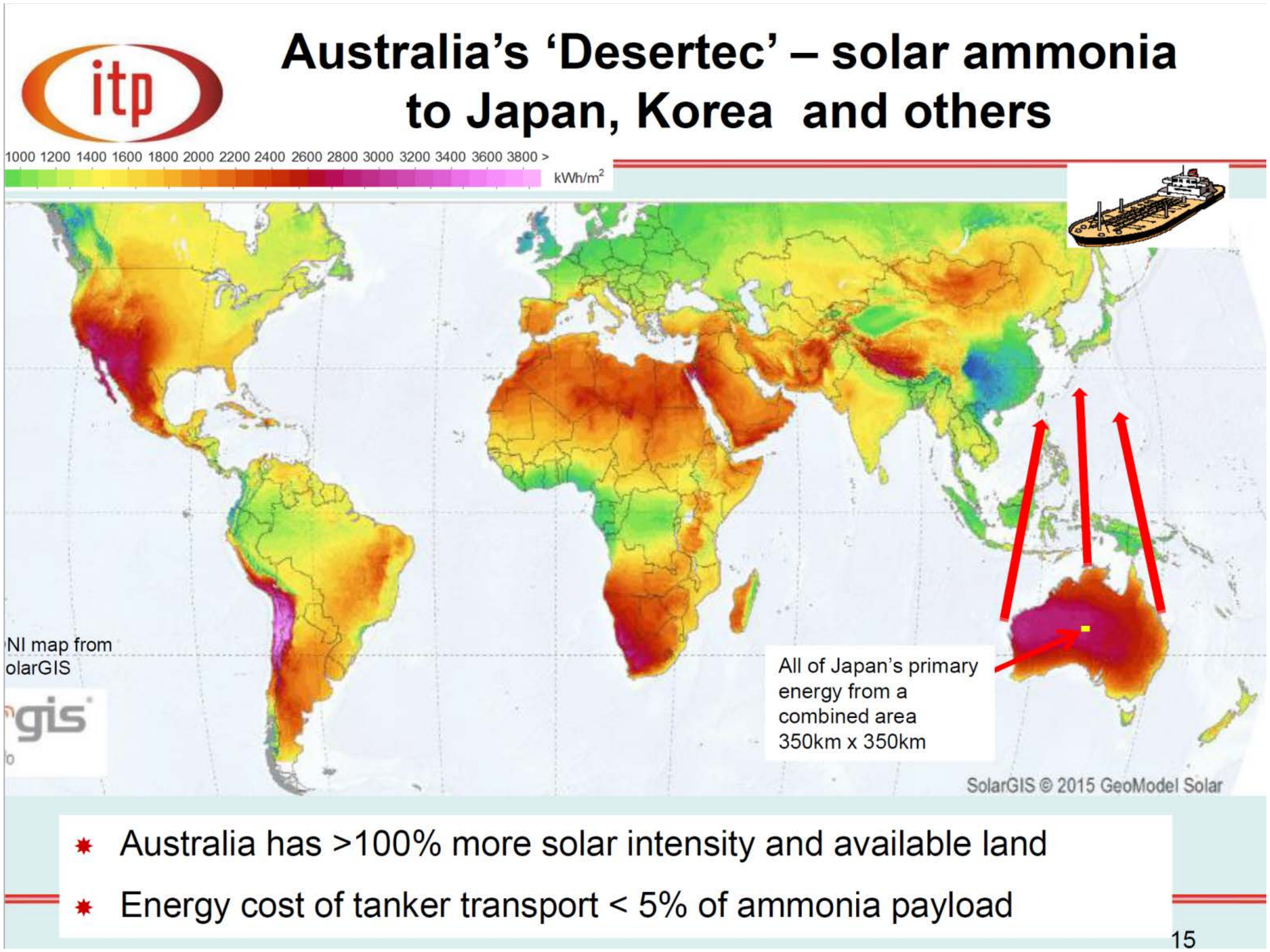
Ultimately: New Global Energy Trading System

- In a remade global energy system, regions rich in renewables would be linked to energy markets in the way major oil exporting countries are today
- Japan and Australia are exploring this concept today



Source: Lovegrove, IT Power Group, NH3 Fuel Conference 2016

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Ammonia provides smallest footprint and CAPEX

Energy storage comparison

30,000 gallon underground tank contains 200 MWh (plus 600 MMBTU CHP heat

Capital cost ~$100K

=

204 MWh NGK battery in Japan

or

40 x

5 MWh A123 battery in Chile

Capital cost $50,000 - 100,000K

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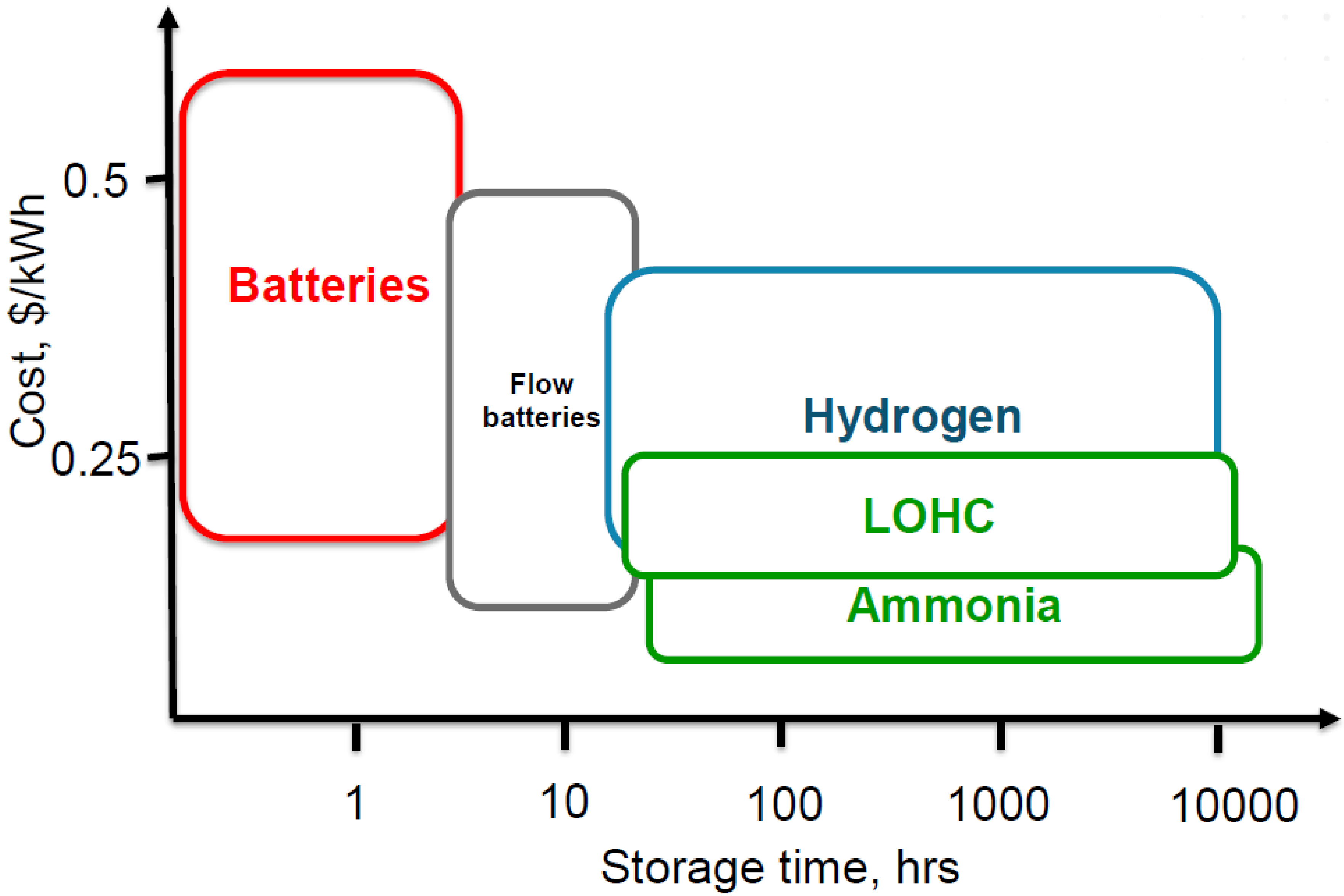
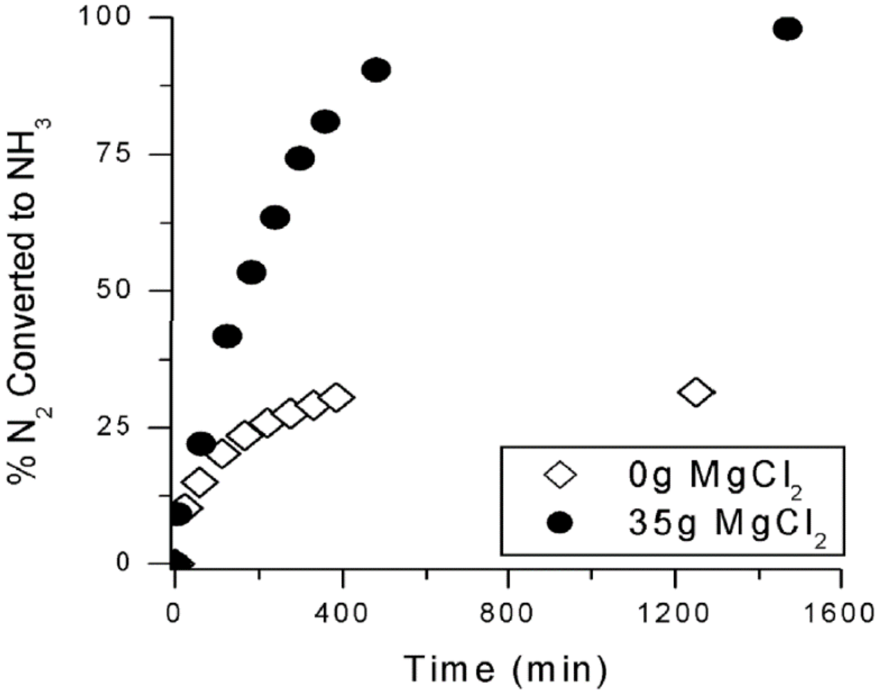
Source: Soloveichik , NH3 Fuel Conference 2016

Levelized cost of energy storage



Research needs: improving ammonia production, via lower pressure and higher conversion efficiency

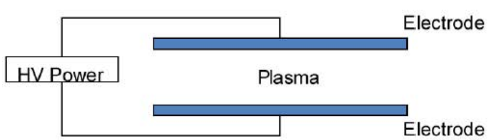


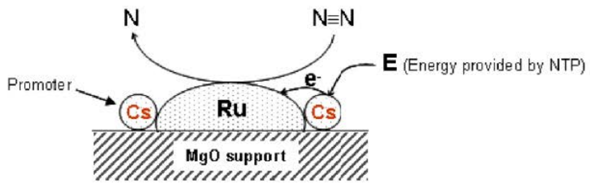
MgCl$_2$ Absorbent Enhanced Ammonia Synthesis

UNIVERSITY OF MINNESOTA
Driven to Discover

Non-Thermal Plasma Assisted Catalysis

- NTP - energized ions and highly reactive radicals made in *non pressurized* gas with electrical discharge
- Catalyst with Promoter: triple bond of dinitrogen weakened by passing electron into the anti-bonding orbital of N_2 through the d-orbital of Ruthenium

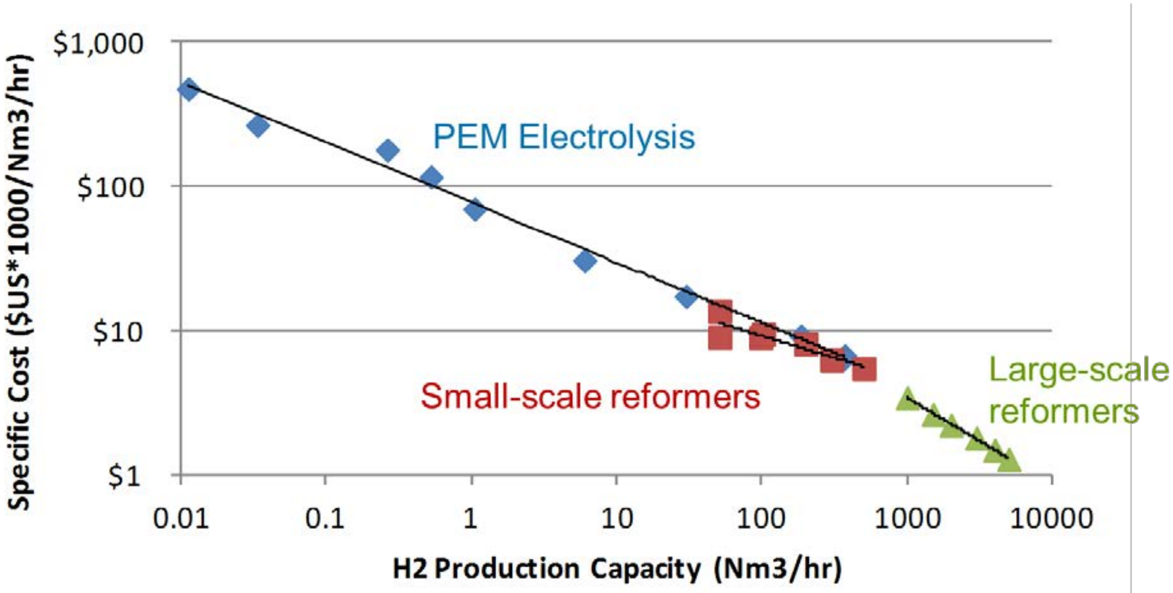


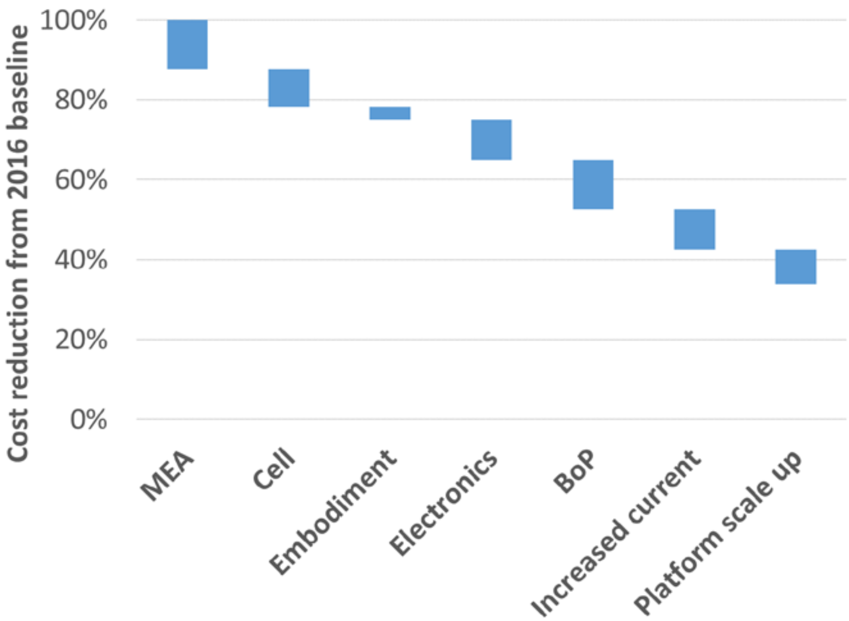


Source: McCormick, University of Minnesota, NH3 Fuel Conference 2015

Research needs: large scale, renewable H_2

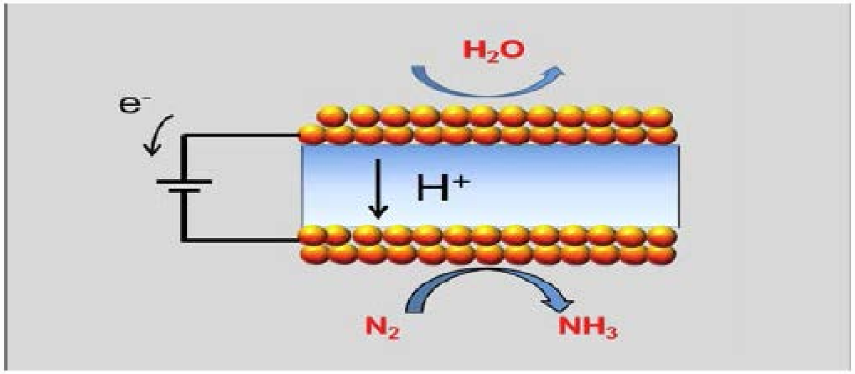
- Smallest HB reactors are 3-10 tons/day
- Larger reactors are currently more cost effective
- Distributed options will need advancements for both steps
  - H2 production scale up; efficient scaled down HB
- Electrolysis shows capital cost pathway but work is needed across multiple areas



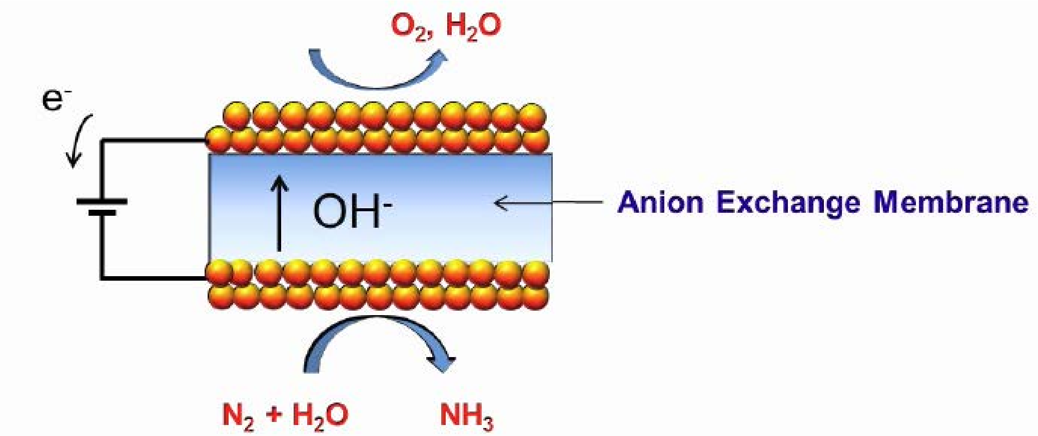


Research needs: electrochemical ammonia synthesis

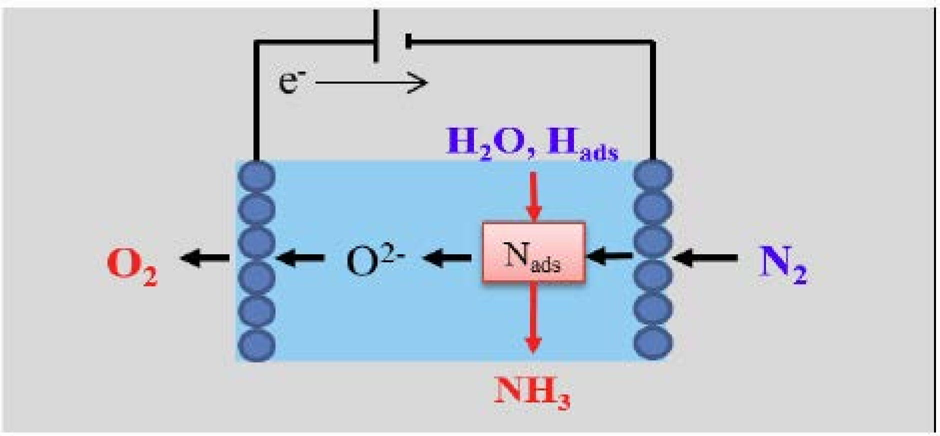
Key Challenges:
- Selective catalysts
- Faradaic efficiency that competes with Haber Bosch
- Durability and stability of materials



PEM synthesis cell



AEM synthesis cell



Liquid state synthesis cell

High temperature pathways exist for acid and base options as well

Research needs: efficient H2 recovery through electrochemical & catalytic methods

- Anode: Ammonia Oxidation

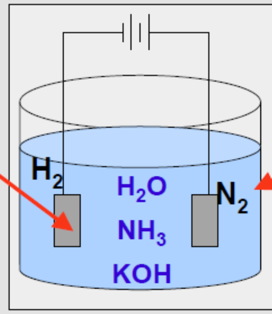
$$2NH_3 + 6OH^- \rightarrow N_2 + 6H_2O + 6e^- \quad E^0 = -0.77 \text{ vs SHE}$$

- Cathode: Water Reduction

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad E^0 = 0.82 \text{ V vs SHE}$$

- Overall Reaction

$$2NH_3 \rightarrow N_2 + 3H_2 \quad E^0 = 0.059 \text{ V}$$

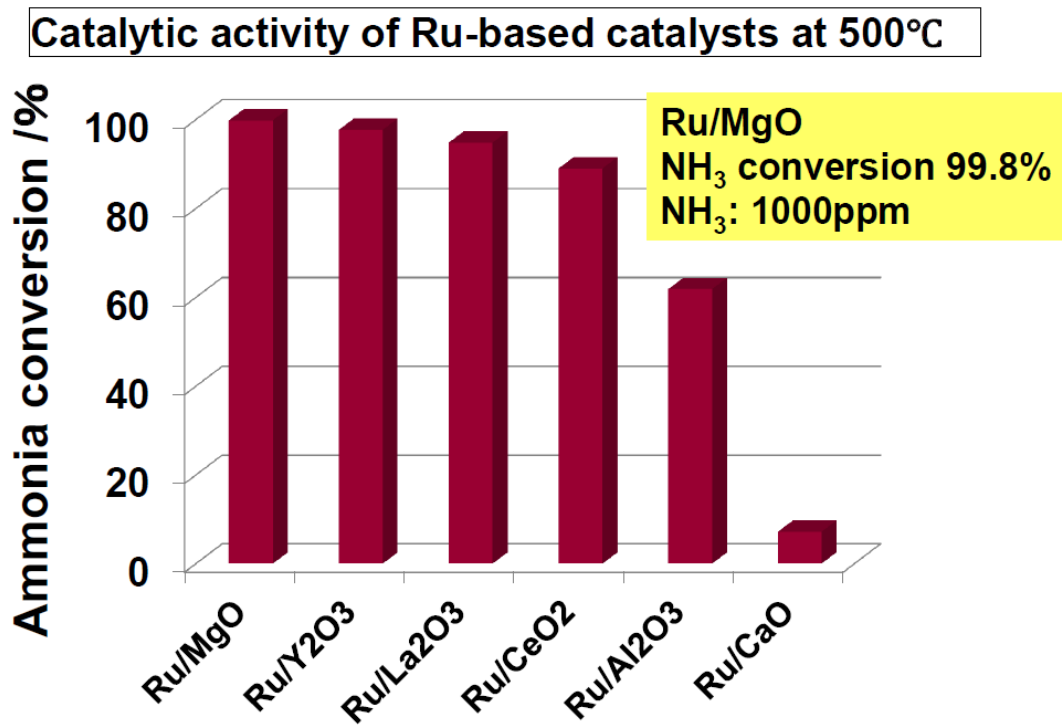


Electrolysis of NH3 to H2

Source: Botte, NH3 Fuel Conference 2015

Breakthrough in cracking catalyst design

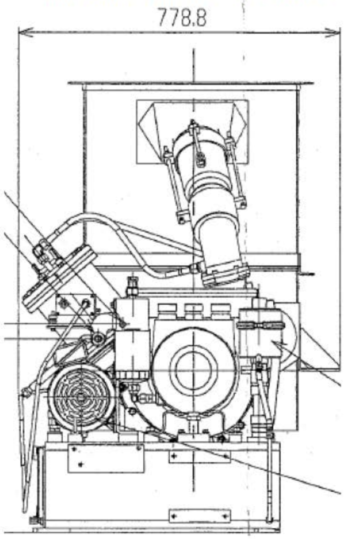
Source: Kojima, NH3 Fuel Conference 2015



Research needs: direct ammonia utilization

Base Micro Gas Turbine

- A 50kW class micro gas turbine was selected as the base engine of ammonia fueled gas turbine.
- This gas turbine was made by TOYOTA TURBINE AND SYSTEMS INC (TTS).



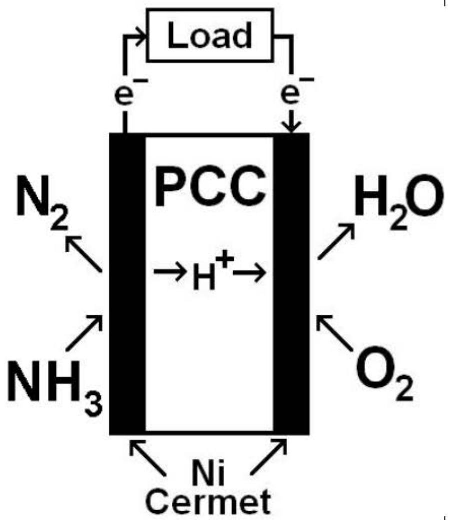
Specification of base micro gas turbine

Manufacturer	Toyota Turbine and System Inc. (TTS)
Cycle	Regenerative cycle
Shaft	Single shaft
Compressor	Centrifugal one-stage
Turbine	Radial one-stage
Rotating Speed	80,000rpm
Electric Power Output	50kW
Fuel	Kerosene
Combustor	Single can, Diffusion combustion

Ammonia fueled combustion

Source: Iki, et al, AIST, NH3 Fuel Conference 2016

- **Utilizes inexpensive base metal catalyst (Ni or Co)**
  - Operating temperature 450-700°C, depending on catalyst
  - Elevated temperature increases electrode kinetics
- **Complete ammonia conversion IS possible!**
- **Fuel not diluted by steam**
- **NO_x-free exhaust**



Direct ammonia fuel cell

Source: Ganley, Howard University

Key Takeaways

- Carbon free ammonia needs to be a significant contributor to the H2@Scale initiative.
- Renewable ammonia production will directly benefit from electrolysis technology and cost improvements in development.
- Ammonia can play a dual role as both a life sustaining commodity, as well as an efficient energy carrier and fuel.
- Distributed ammonia production can be located in areas with both high RE resources and high fertilizer demand.