Rural Minnesota Energy Board (RMEB) Meeting

Green Hydrogen and Ammonia: Implications for Minnesota and Beyond

September 25, 2023

Presented by:
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College of Food, Agricultural and Natural Resource Sciences
University of Minnesota

West Central Research & Outreach Center
"Leading innovation in agriculture and beyond"

Acknowledgements

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- University of Minnesota College of Food, Agricultural, and Natural Resource Sciences (CFANS)
- Clean Energy Resource Teams (CERTS)
- Electric Power Research Institute (EPRI)
- MnDRIVE
- Xcel Energy

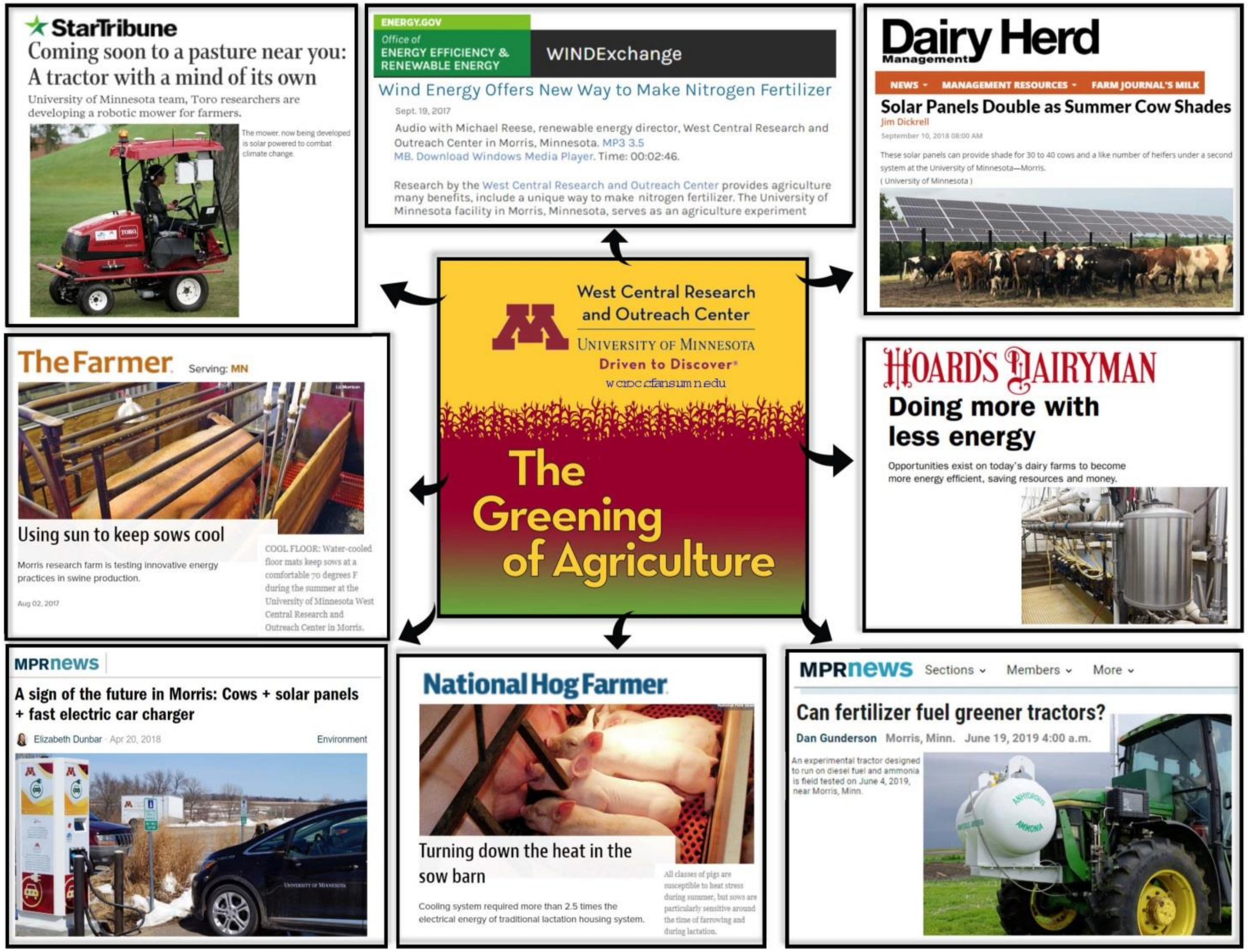
Program Goal: Reduce fossil energy consumption in production agriculture

- 20 to 25 % of GHG in Minnesota and the world attributed to agriculture, forestry, and related industries

  (MPCA, 2016; IPCC, 2017)

- 2% global GHG emissions attributed to ammonia and nitrogen fertilizer production

- Markets and policies are trending towards the need for GHG reductions in production agriculture



WCROC IMPACT: National and regional recognition

The Washington Post

StarTribune

The New York Times

Throwing Shade Is Solar Energy's New Superpower

Analysis by Adam Minter | Bloomberg   October 3, 2022 at 12:44 a.m. EDT

Could solar panels be integrated into farms instead of taking acreage out of commission?

By Nick Williams Star Tribune | OCTOBER 15, 2022 — 3:51PM

As Federal Climate-Fighting Tools Are Taken Away, Cities and States Step Up

By Maggie Astor   Published July 1, 2022   Updated July 7, 2022

WCROC IMPACT: State recognition

STATE OF MINNESOTA
Executive Department

Governor Tim Walz

Executive Order 22-22

Directing State Agencies to Pursue Federal Funding for Clean Hydrogen Market Development in Minnesota

> “Development of hydrogen markets in Minnesota would build on successes such as those seen at the University of Minnesota’s West Central Research and Outreach Center in Morris, which has been a global leader…”

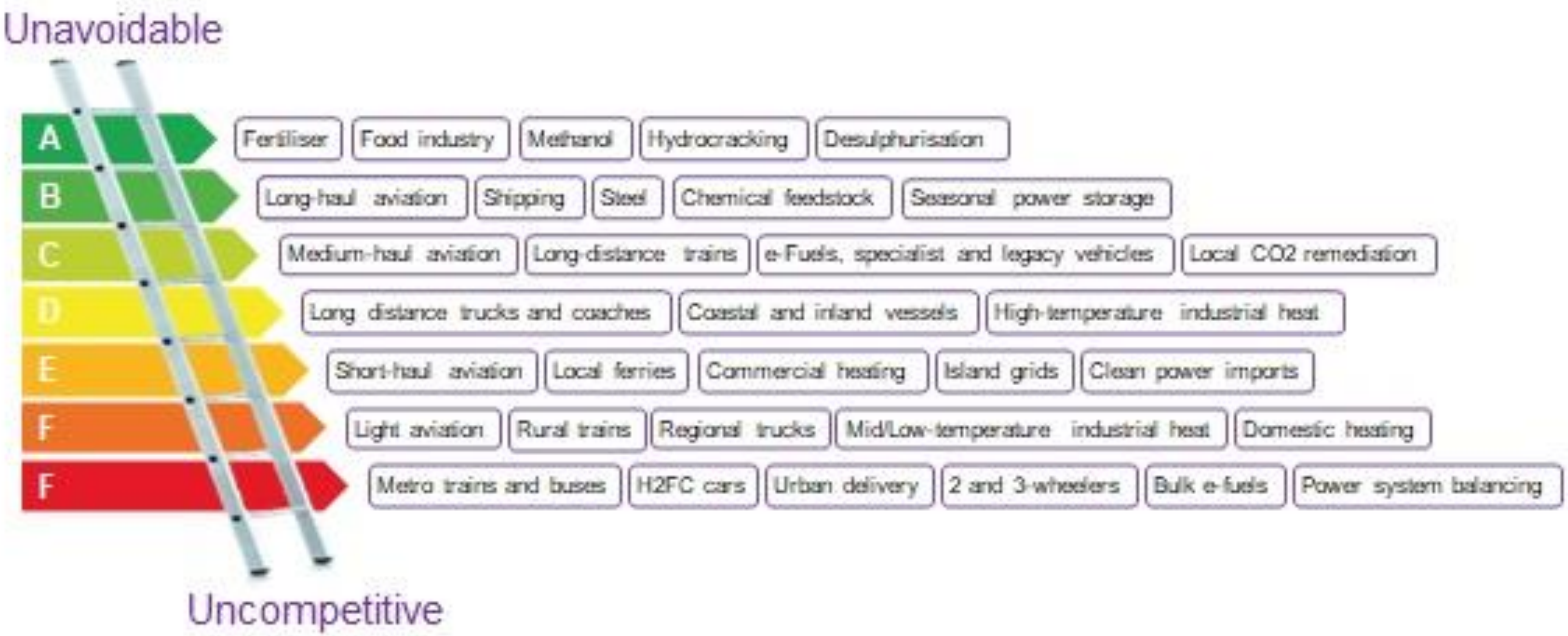
Decarbonizing Midwest Industry and Utilities using Zero-Carbon Hydrogen

Climbing the green hydrogen use-case ladder in the Midwest:

1. **Agriculture** – Drop-in green ammonia and urea fertilizer; use ammonia for fueling grain drying, tractors, and trucks.
2. **Power generation and thermal energy** - Fuel gas turbines, engine gensets, and burners and boilers.
3. **Biofuel production** – Use green hydrogen for production of renewable diesel, jet fuel (SAF), methanol, and ethanol. Capture and recycle CO_2 normally emitted via fermentation to produce these fuels.
4. **Medium and Heavy Transportation Industry** – Switch to hydrogen and ammonia to fuel trucks, mining equipment, tractors, train engines, and ships.
5. **Mining and Steel Making** – Displace energy used in processing ore into iron pellets as well as the carbon purification process within steel making. Currently responsible for 8% of global GHG emissions.
6. **Construction** – Use hydrogen and-/- or ammonia to heat kilns used in the production of quick lime. Capture CO2 released during heating of limestone for urea or renewable fuels production.

Hydrogen: The Use Case Ladder

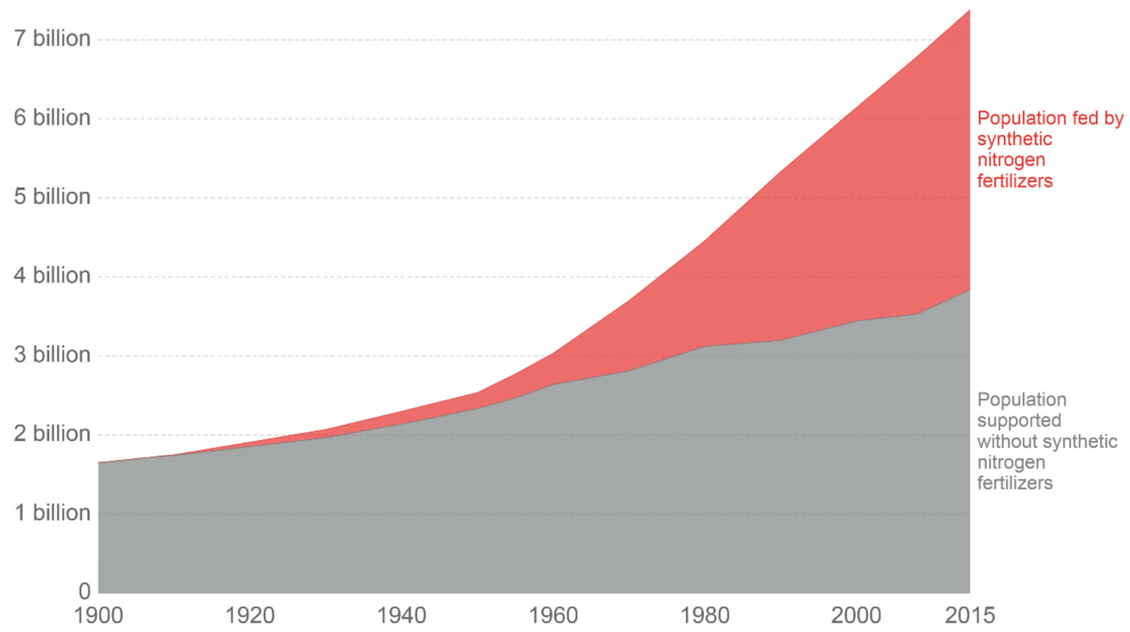
Liebreich Associates



Source: Liebreich Associates Concept: Adrian Hiel/Energy Cities

Ammonia: Feeding the World by Supplying Nitrogen for Grain Production

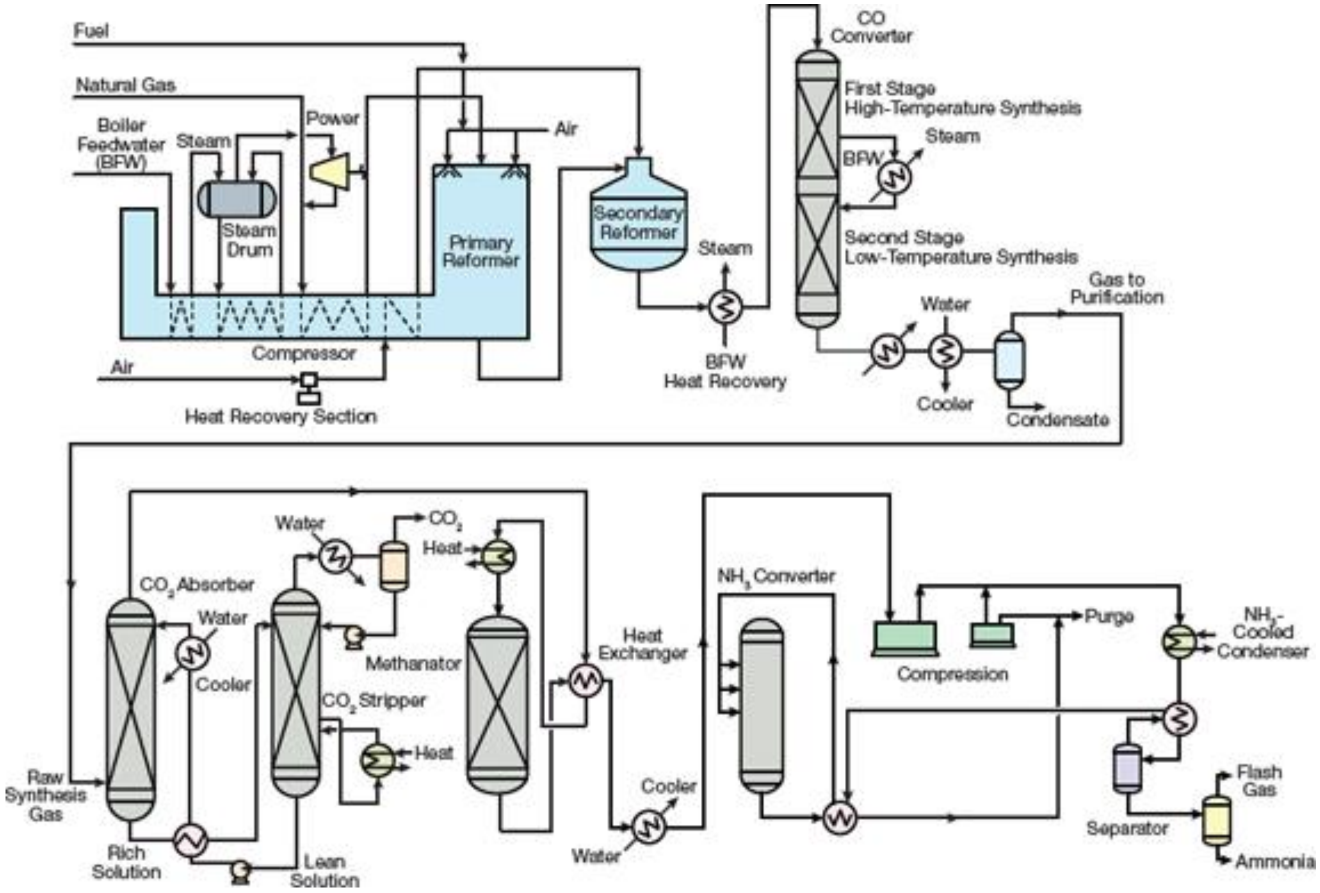
- Anhydrous Ammonia (NH_3): Backbone of nitrogen fertilizer
- Next to water, most limiting nutrient
- Feeds half of the global population
- Primary feedstock in natural gas (some coal)
- 1% of Global GHG attributed to ammonia production (IPCC, 2017)



Source: Ritchie, *Our World in Data*: https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed#note-4; Erisman et al., 2008, Nat. Geoscience, 1 (10), 636-639.

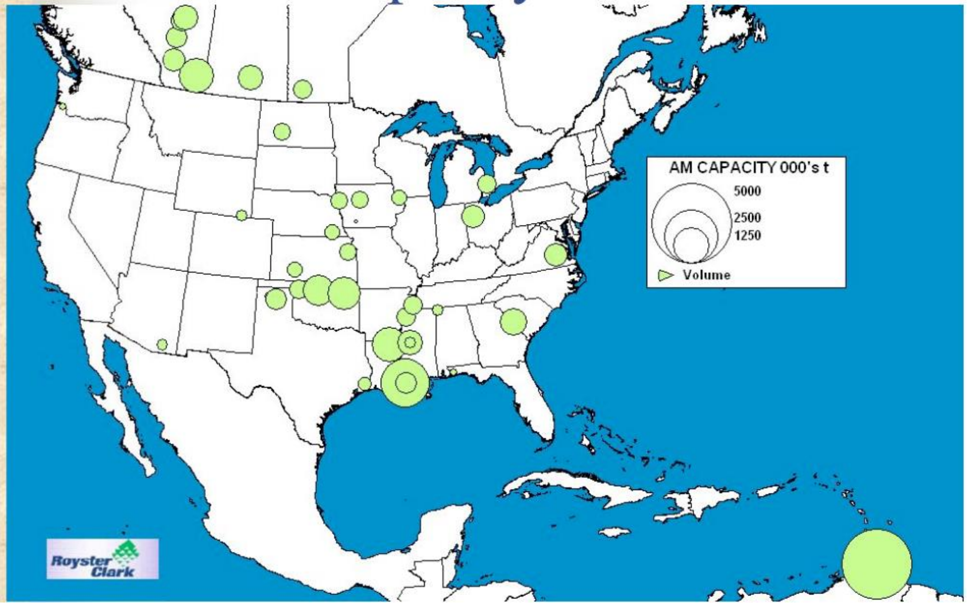
Nitrogen Fertilizer Production Worldwide Predominantly Uses Natural Gas or Coal

- Massive plants largely in the Gulf Coast and Canada
- Use natural gas (SMR) and coal (gasification) as feedstock for hydrogen
- Use roughly 2.3 tons of water per ton of ammonia produced (but some water recovered)
- A portion of the CO_2 is used for production of urea



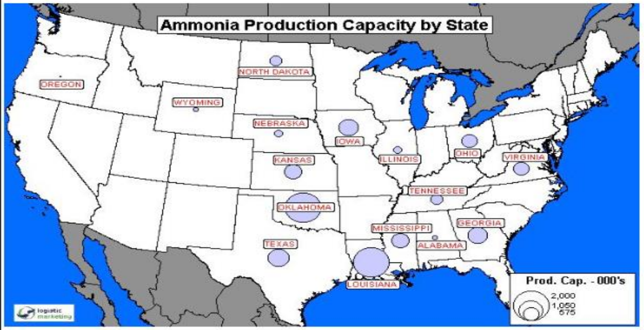
AIChE. 2016

NA Base Capacity



State Production Capacity

State	Capacity Tons	Rank
LA	4,514,000	1
OK	2,515,000	2
AK	1,416,000	3
IA	791,000	4
GA	758,000	5
KS	695,000	6
TX	680,000	7
MS	669,000	8
OH	598,000	9
VA	584,000	10
TN	409,000	11
ND	400,000	12
IL	306,000	13
NE	292,000	14
AL	193,000	15
WY	192,000	16
OR	111,000	17
FL	86,000	18



Ammonia Transportation:

- Pipeline (to regional hubs)
- Barge (Up the Mississippi)
- Train (To regional storage facilities)
- Truck (to local ag input retailers)
- Nurse tanks (to farms)

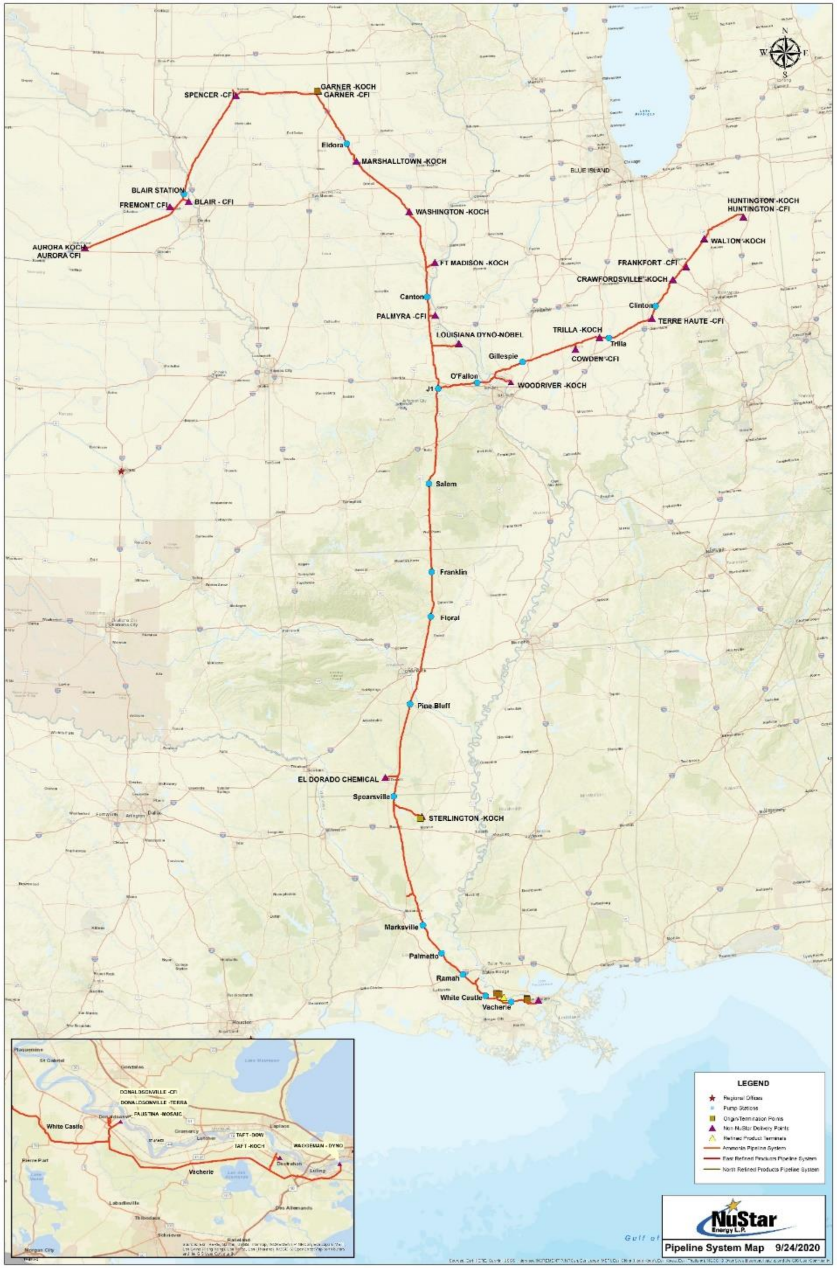
Ammonia Storage:

- Regional large refrigerated storage tanks (30,000 to 90,000 tons)
- Local ag input / fertilizer retailers (40 to 200 tons)

Storage, Transport, Use Concerns

- **Inhalation hazard**
- **High nitrates in ground water**
- **Greenhouse gas itself**

Safer than hydrogen as a fuel and storage medium



Cost Targets and Formulations for Common Ag Fertilizers:

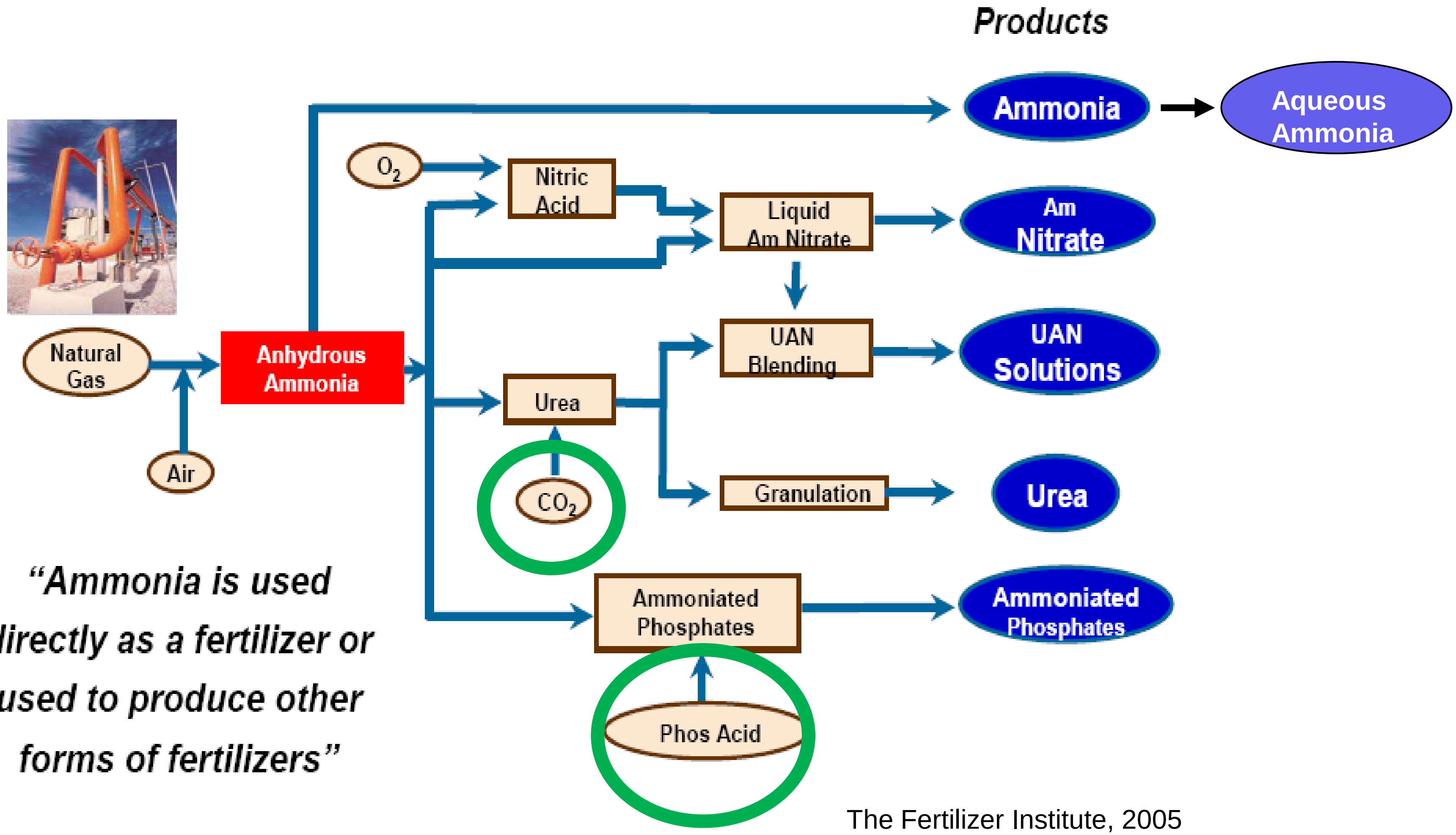
- ✓ Nearly all synthetic forms of N fertilizer use ammonia (NH3) in the production process
- ✓ US nitrogen fertilizer market is roughly a $6 billion industry
- ✓ Minnesota farmers spend between $500 million to $1 billion per year on N fertilizer
- ✓ Farmers could participate in ownership of green ammonia production

US Retail Agricultural Fertilizer Prices

Common Fertilizer Types	N-P-K or Percent Available	Retail Price / Short Ton[1]
Anhydrous Ammonia (NH3)	82-0-0	$450
Urea	46-0-0	$360
UAN 28% Liquid	28-0-0	$275
MAP	11-52-0	$455
DAP	18-46-0	$430
Potash	0-0-60	$330
Sulfur	90%	$1,000
Zinc	35%	$2,000
Boron	12%	$2,000

[1](11/10/2020 retail prices from a Minnesota ag cooperative)

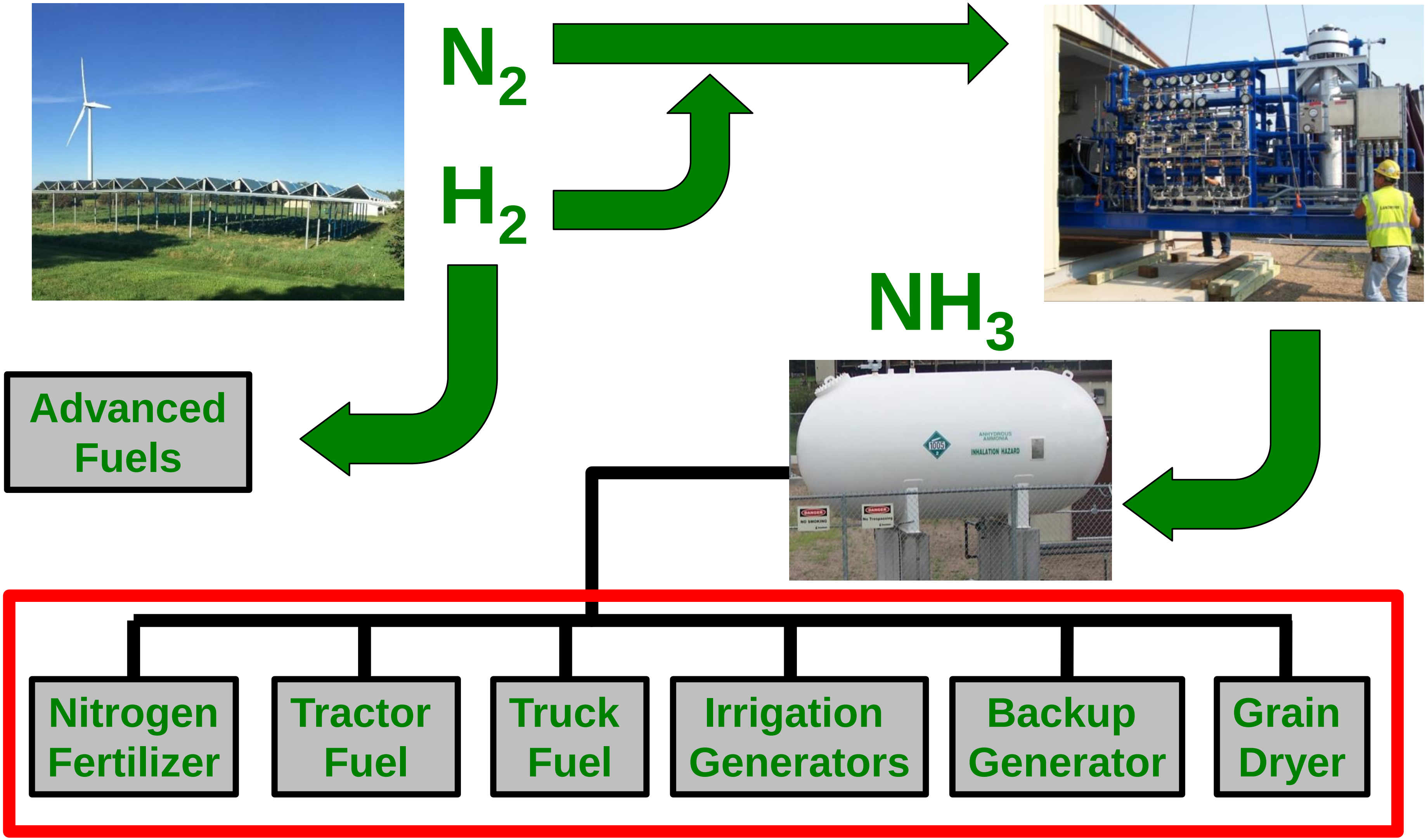
Nitrogen Fertilizer Production



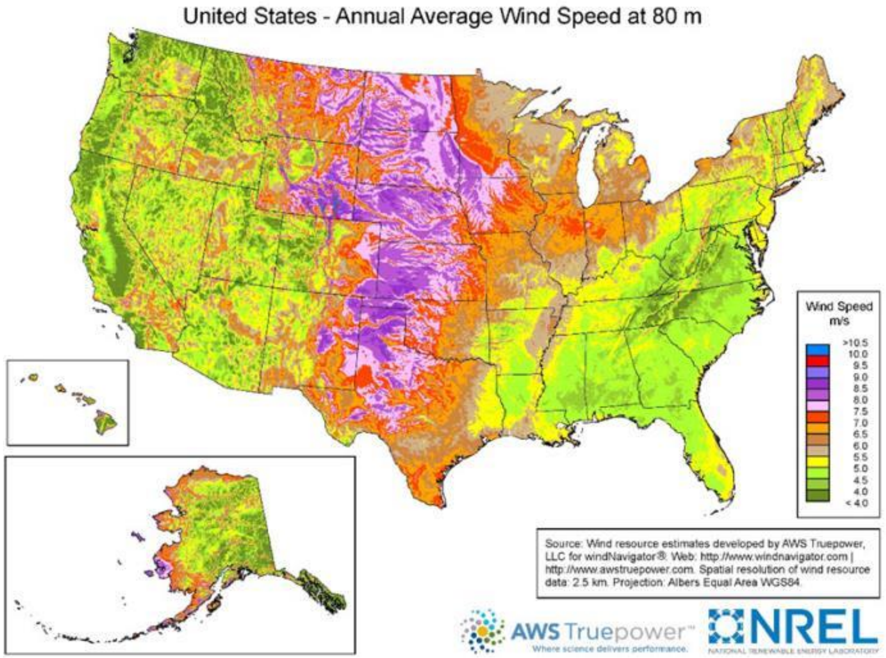
"Ammonia is used directly as a fertilizer or used to produce other forms of fertilizers"

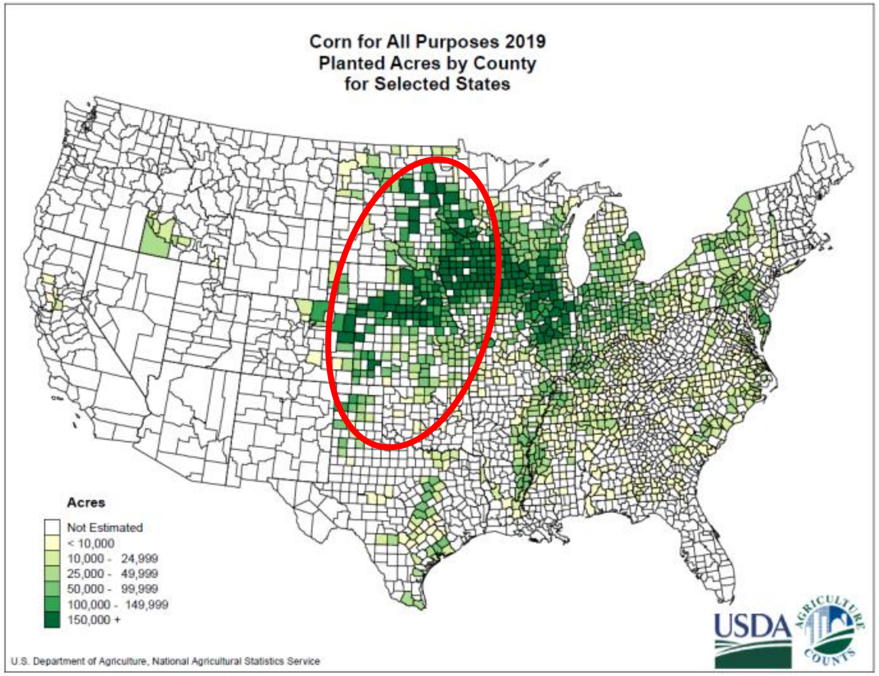
The Fertilizer Institute, 2005

Green Ammonia: De-carbonizing and transforming farm energy



Scale: Green Ammonia

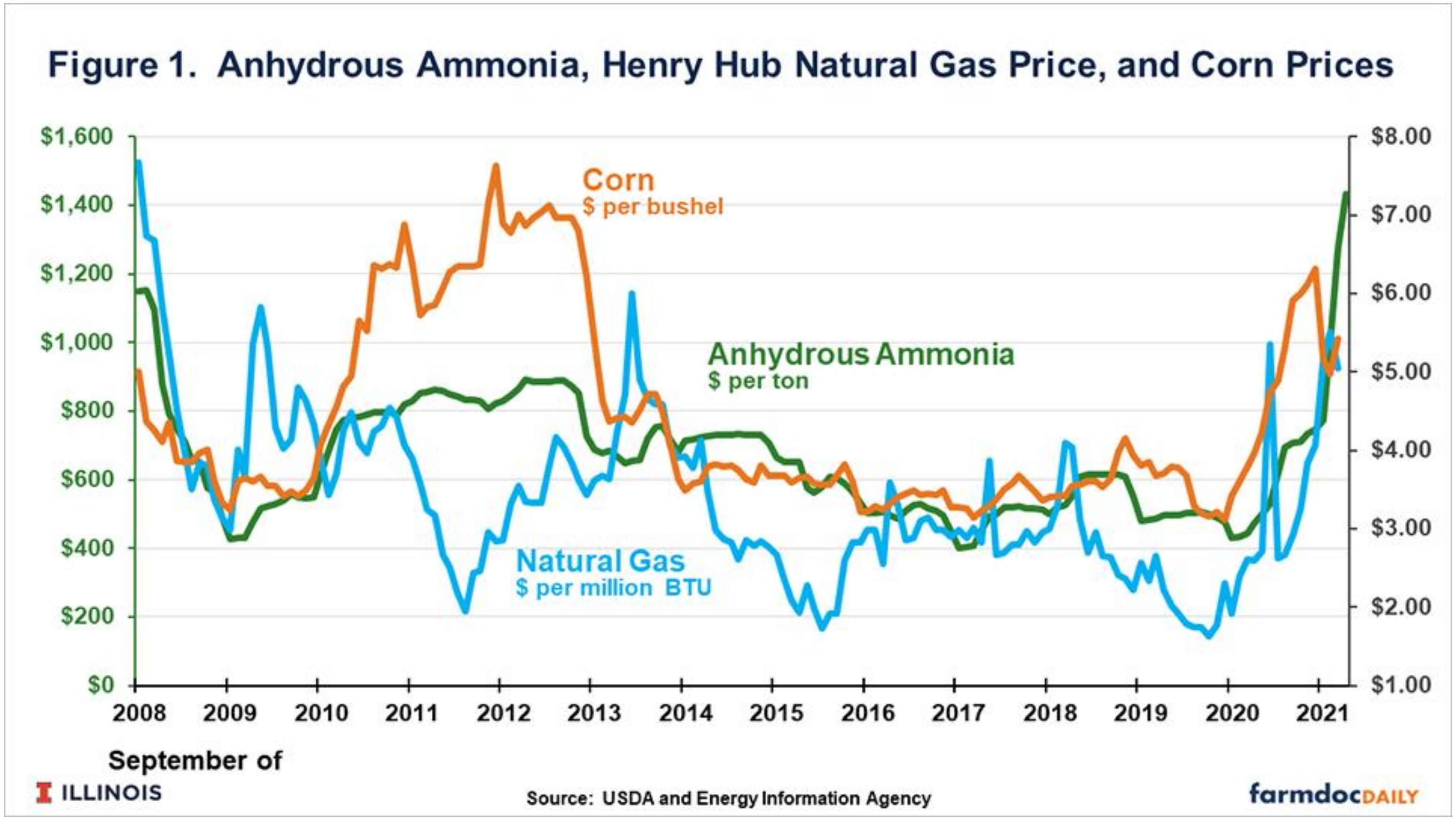




- US wind resource is synergistic with Midwest corn production and nitrogen fertilizer demand – inherently distributed
- US nitrogen fertilizer demand could be met with approximately 50,000 MW of nameplate wind energy capacity – current US wind generation is 105,583 MW of nameplate capacity
- Opportunity to utilize “stranded” wind and solar resources (and excess nuclear)

Why renewable ammonia?

- **Price certainty and stability, decoupling from global natural gas market**
- **Reduce carbon intensity: >2.6 mt_{CO2}/mt to <0.2 mt_{CO2}/mt**
- **United States: Federal clean H_2 production credits up to $3/kg**
  - **$529/mt ammonia production credit for first 10 years of production!**



Palys, et. al. 2022

Green Ammonia: An Elegant Solution

Wind Energy + Water + Air = Nitrogen Fertilizer

Step 1. Electrolysis of Water $2H_2O \longrightarrow 2H_2 + O_2$

Step 2. Air Separation / Pressure Swing Absorption:

Oxygen (O_2) and argon (Ar) are absorbed in a molecular sieve leaving nitrogen $\longrightarrow N_2$

Step 3. Haber or Haber-Bosch Process:

$$N_{2\,(g)} + 3H_{2\,(g)} \rightleftharpoons 2NH_{3(g)} \qquad \triangle H = -92.4\ kJ$$

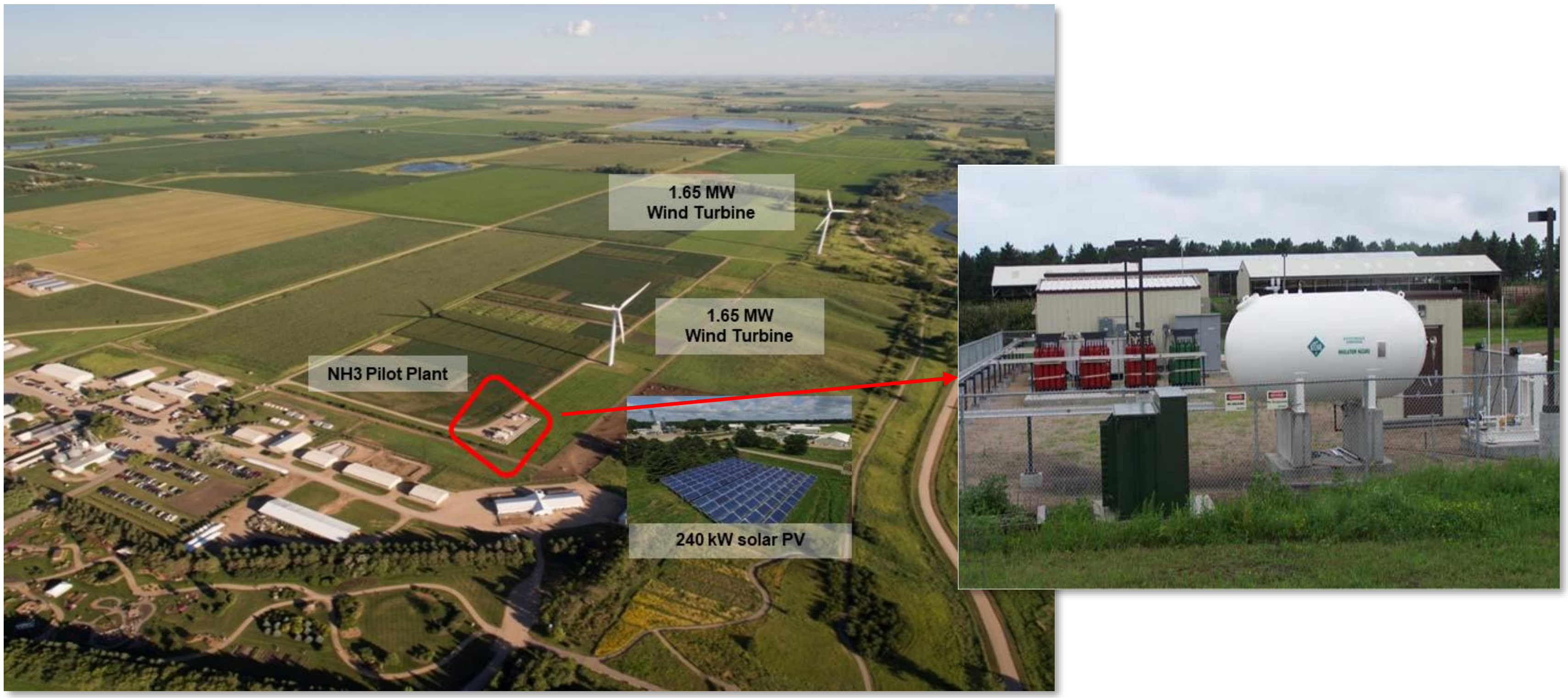
Step 4. Urea Production (CO_2 capture and utilization):

$2NH_3 + CO_2 \rightarrow NH_2COONH_4$ (ammonium carbamate)

$NH_2COONH_4 \rightarrow H_2O + NH_2CONH_2$ (urea)

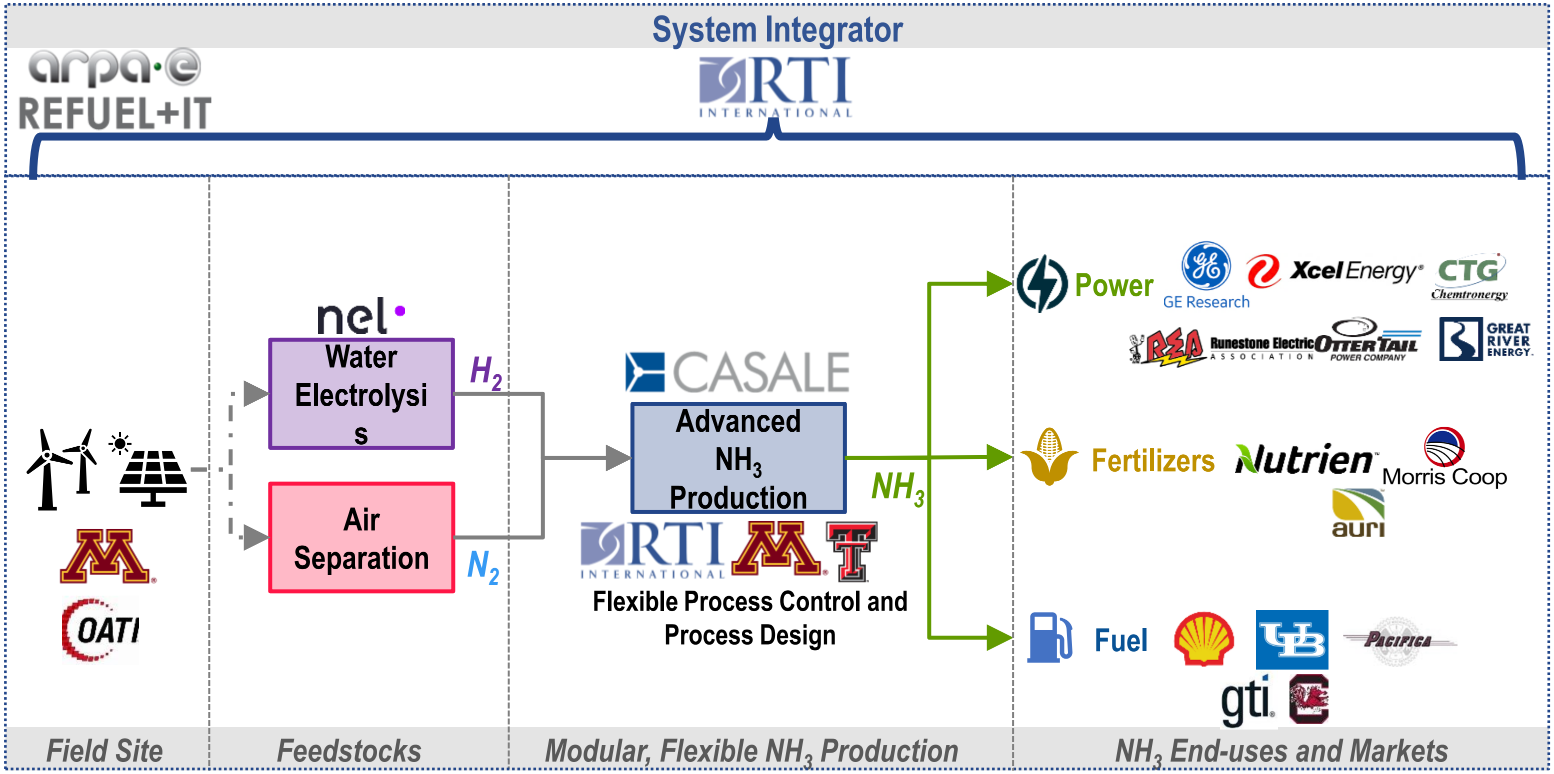
- Use CO_2 from bioethanol fermentation
- circular model

Research to improve efficiency:
US DOE ARPA-E REFUEL Technology Integration Project



~18x scale-up of existing wind-to-NH_3 pilot plant

Next Generation Ammonia Production from Wind and Solar



Next-gen NH_3 production and utilization technologies	Demonstrate under real-world conditions	Connect with end-users and markets to accelerate commercialization

What are we doing with the Ammonia?

Power

Retrofit options for aeroderivative gas turbine to burn NH_3

Demonstrate a 1-kW direct NH_3 fuel cell

Fuel

Develop and operate a NH_3-powered forklift

- High purity H_2 from NH_3 cracking membrane
- Retrofit fuel cell powered forklift

Fertilizers

Off-take agreement with local fertilizer co-op

Morris Coop

- Portable engine genset / non-wire solutions
- Grain dryer
- HRSG duct burner

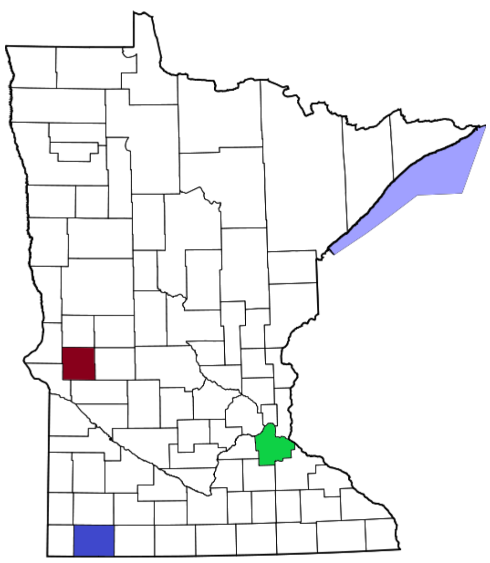
- Ammonia-fueled tractor

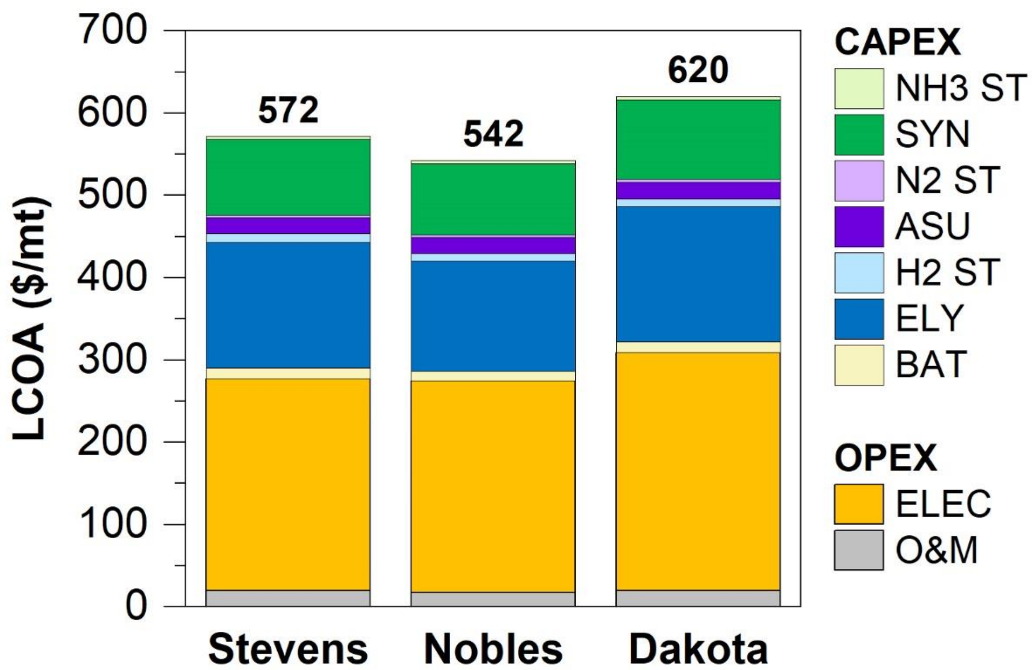
Demonstrating the full value chain of low- and zero-carbon Ammonia

Production cost depends on location

- **Stevens county: 44% wind, 15% PV**
- **Nobles county: 52% wind, 16% PV → *-$30/mt* than Stevens**
- **Dakota county: 36% wind, 15% PV → *+$50/mt* than Stevens**

Does not include $529 / metric ton NH_3 value from H_2 incentive!



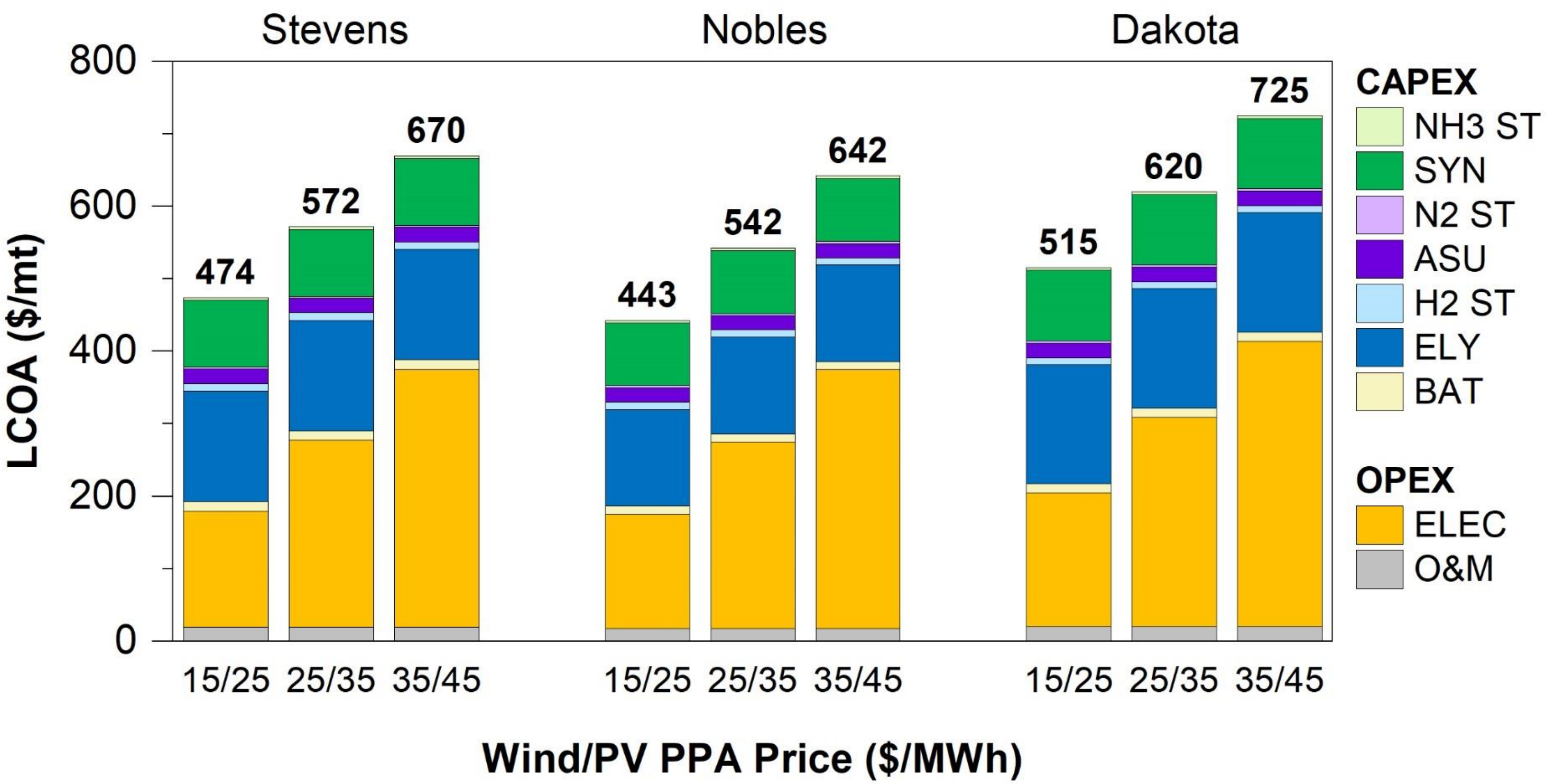


Design for each location to minimize LCOA

Palys, et. al. 2022

Production cost depends on energy price

Does not include \$529 / metric ton NH_3 value from H_2 incentive!



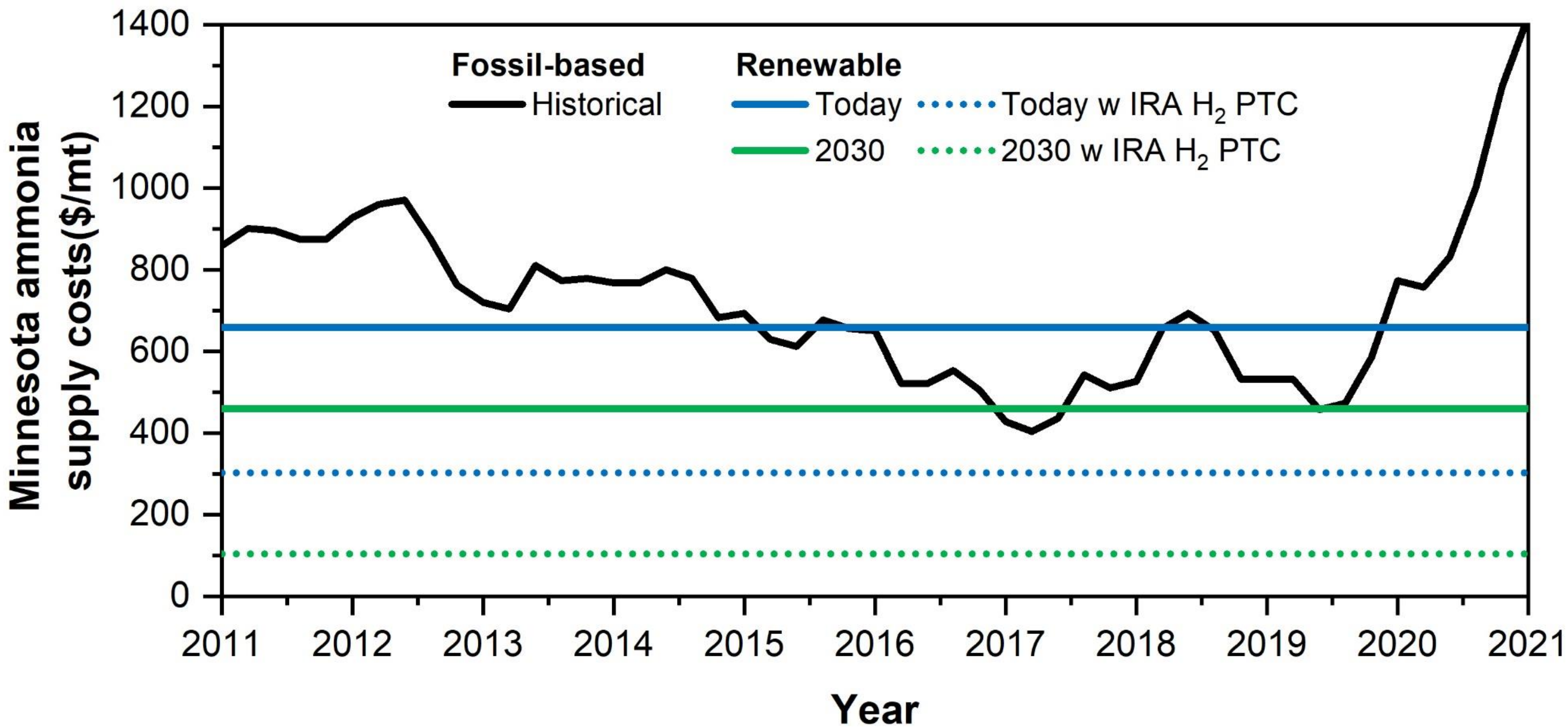
Impact of energy price: Δ\$10/MWh → Δ\$100/mt

Palys, et. al. 2022

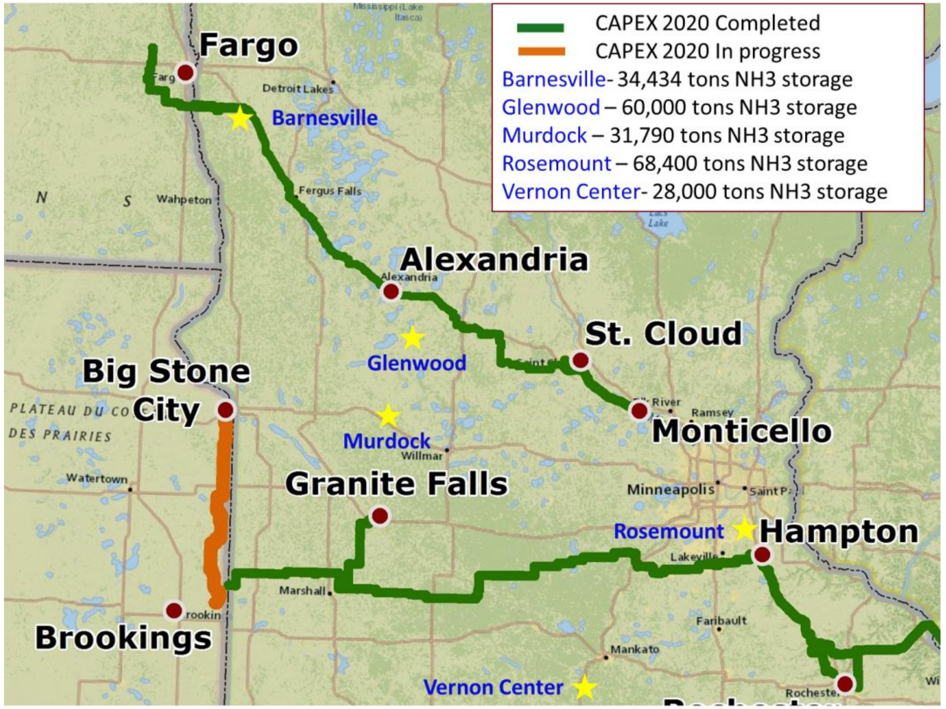
IRA H_2 PTC is transformative

IRA: \$3/kg H2 credit for CI<0.45 kg_{CO2}/kg_{H2}, labor/wage requirements met

- **\$529/mt ammonia for first 10 years of production (ammonia CI<0.08 mt_{CO2}/mt_{NH3})**
- **\$356/mt ammonia levelized over 20 year project with 7.5% discount rate**



Large-scale ammonia storage is already in place:

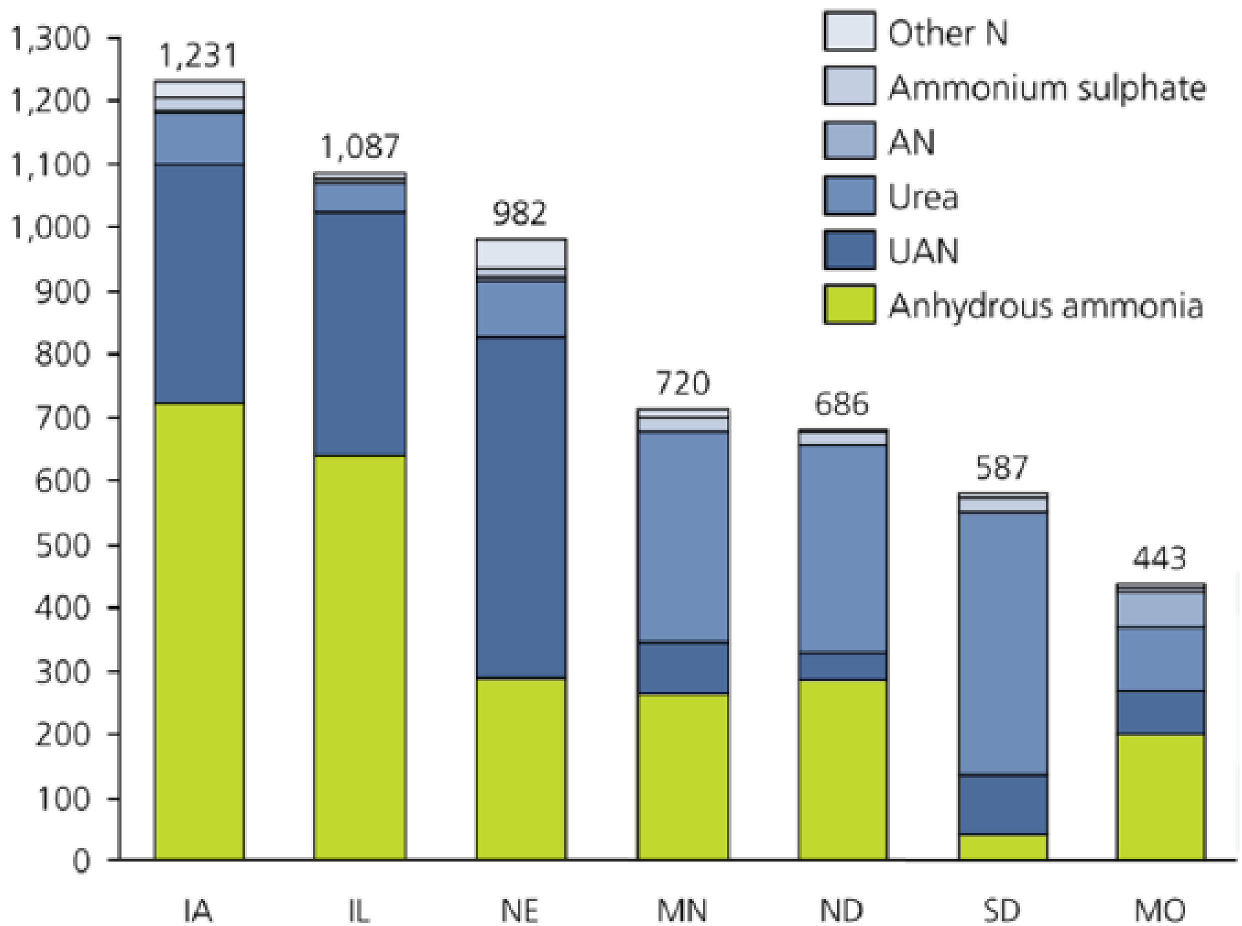


CF Industries Glenwood Ammonia Terminal

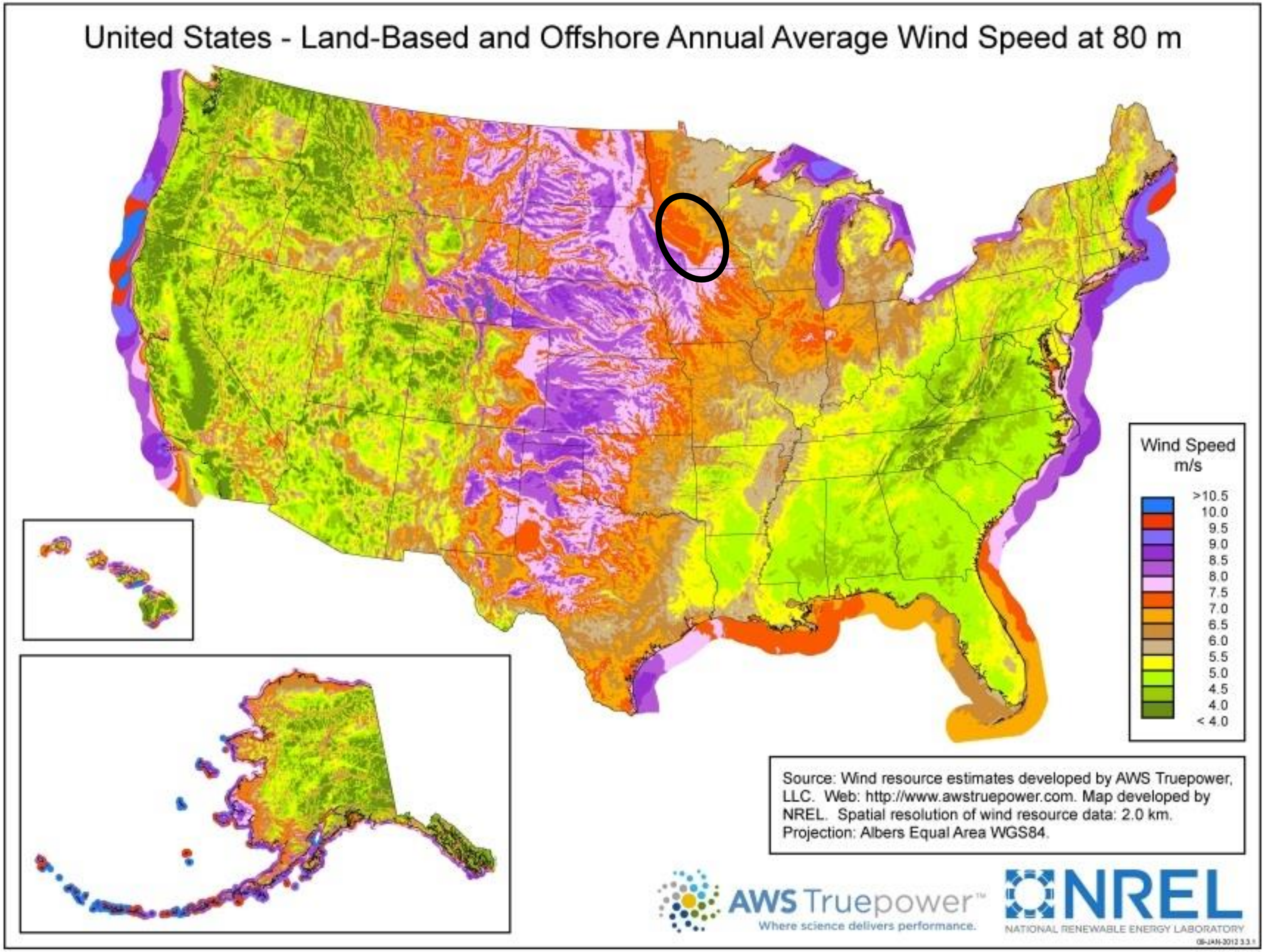
- **Capacity of 60,000 tons of NH_3**
- **Equivalent to an estimated 111,000 MWh of electricity**
- **Wind and solar PV in close proximity**
- **Capex 500 kV line in close proximity**
- **Hub for wind energy transmission**

Green ammonia for N fertilizer:

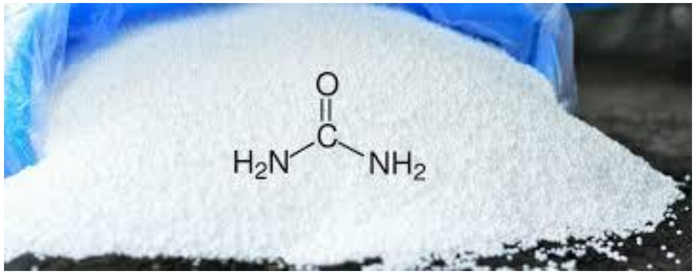
Breakdown of N fertilizer use by State



Source: AAPFCO


United States - Land-Based and Offshore Annual Average Wind Speed at 80 m
Wind Speed
m/s
>10.5
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
< 4.0
Source: Wind resource estimates developed by AWS Truepower, LLC. Web: http://www.awstruepower.com. Map developed by NREL. Spatial resolution of wind resource data: 2.0 km. Projection: Albers Equal Area WGS84.
AWS Truepower™
Where science delivers performance.
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

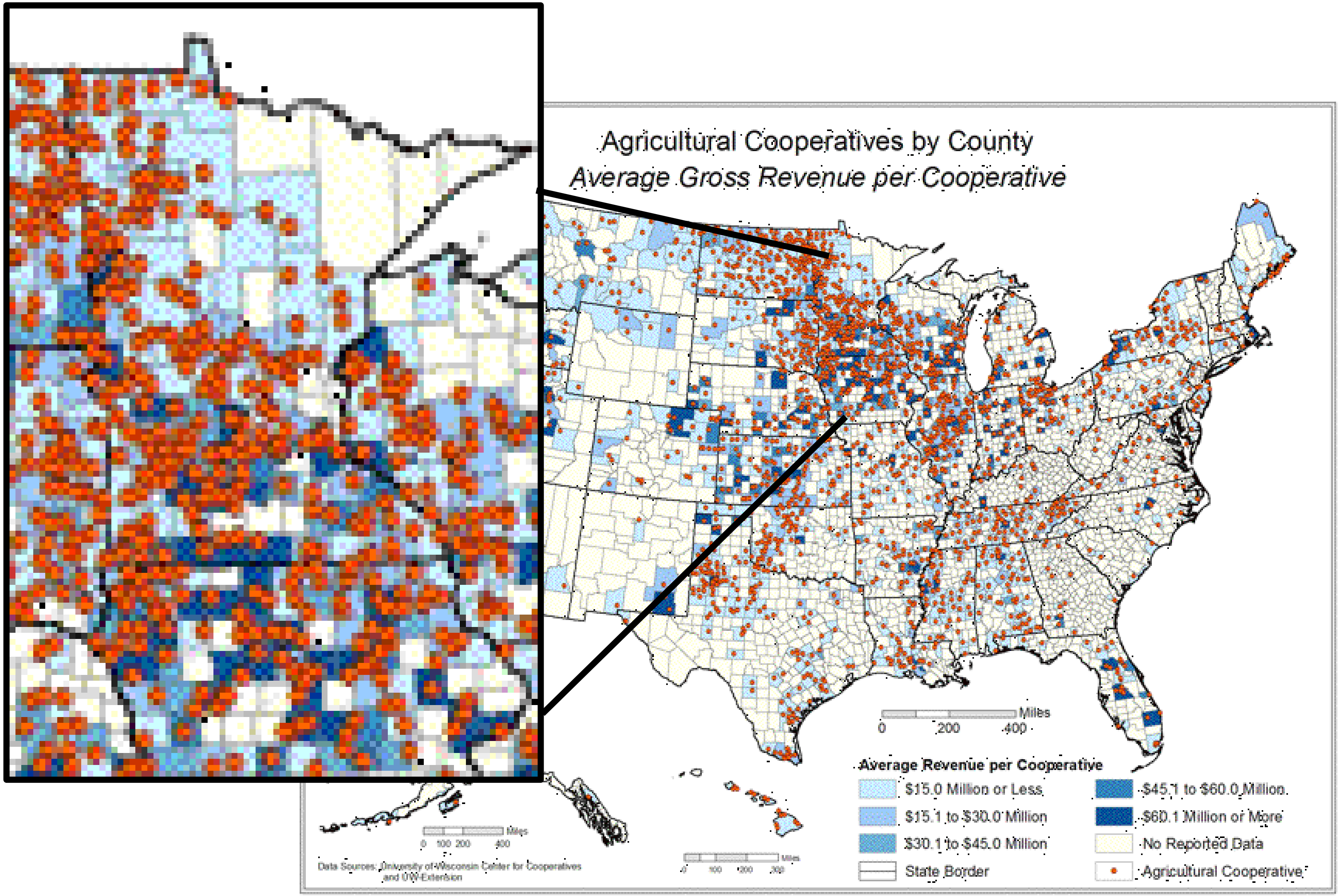
Green urea for N fertilizer:



Significant local infrastructure and market for urea fertilizer:

Westcon

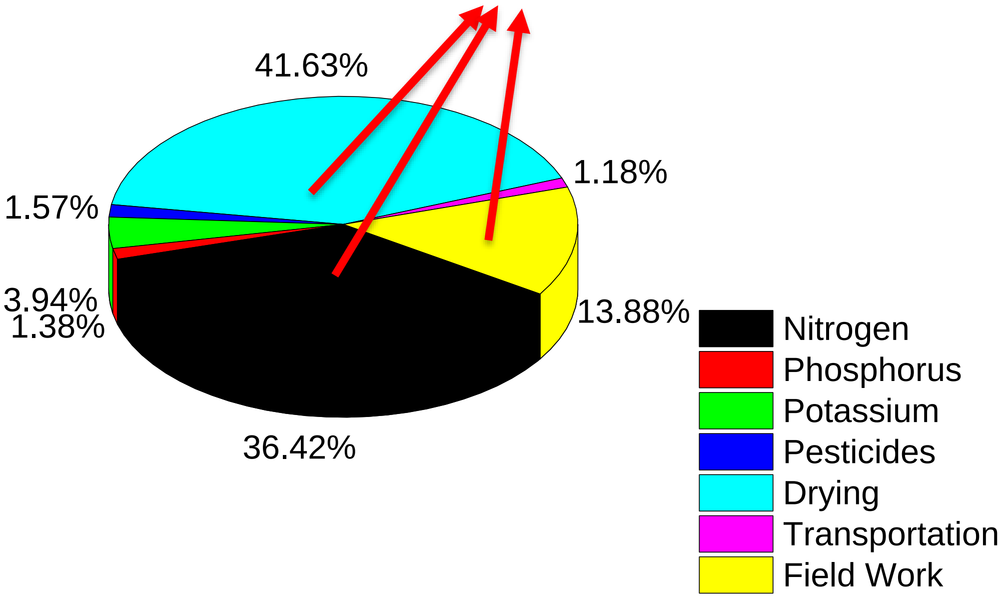
Glacial Plains



Agricultural Cooperatives by County
Average Gross Revenue per Cooperative
Miles
0
200
400
Average Revenue per Cooperative
$15.0 Million or Less
$15.1 to $30.0 Million
$30.1 to $45.0 Million
State Border
$45.1 to $60.0 Million
$60.1 Million or More
No Reported Data
Agricultural Cooperative
Data Sources: University of Wisconsin Center for Cooperatives and UW-Extension

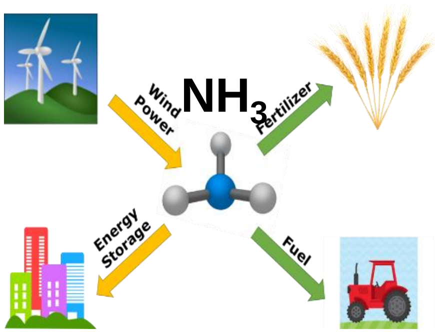
Transformational: Green ammonia is a drop-in replacement

Potential to reduce fossil energy use in corn production over 90% using ammonia (NH_3) produced using wind energy.



J. Tallaksen, 2016. UMN West Central Research and Outreach Center

H_2-based gases and fuels: Is ammonia the new hydrogen carrier?



Name	Molecular Formula (C_nH_{2n+2})	Condensed Structural Formula	Number of Possible Isomers
methane	CH_4	CH_4	—
ethane	C_2H_6	CH_3CH_3	—
propane	C_3H_8	$CH_3CH_2CH_3$	—
butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$	2
pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$	3
hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$	5
heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$	9
octane	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	18
nonane	C_9H_{20}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	35
decane	$C_{10}H_{22}$	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	75

Imagine from Western Oregon University – CH105 Consumer Chemistry Course

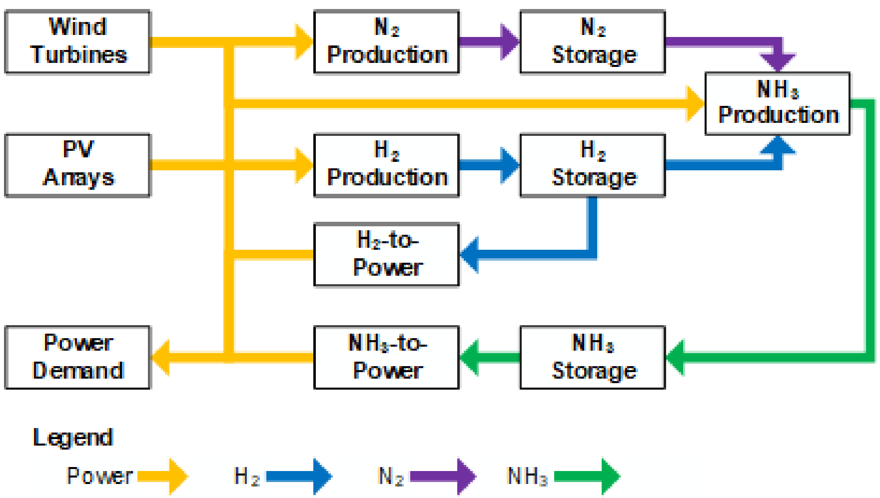
- Ammonia is ten to 100 times less costly to store and transport than hydrogen

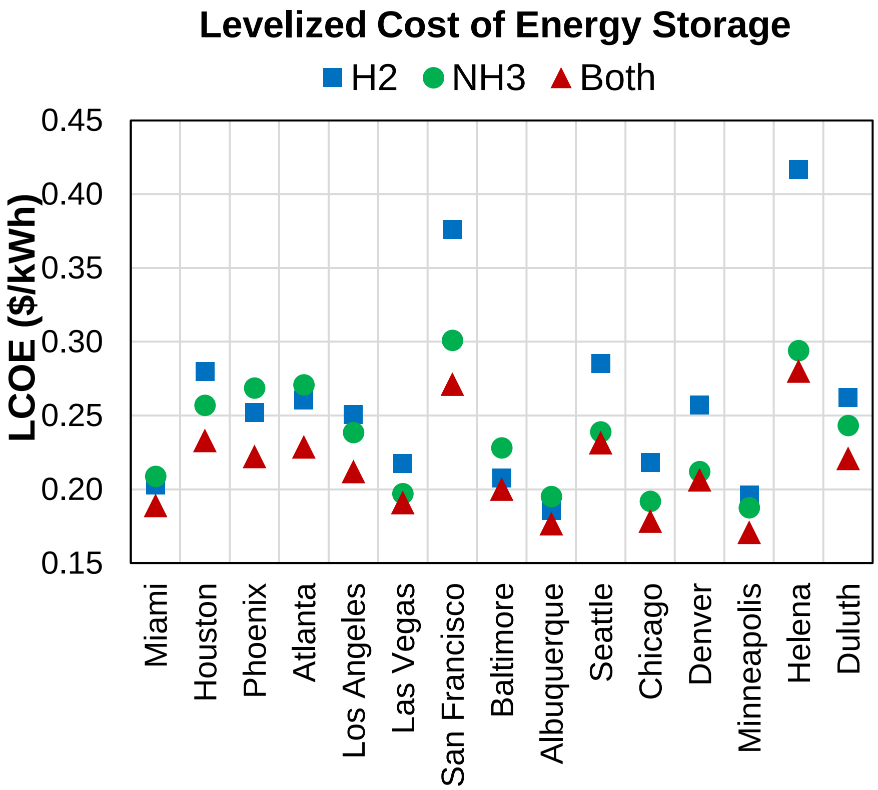
Hydrogen and Ammonia Renewable Energy Storage Systems

Palys & Daoutidis. (2020). *Comput. Chem. Eng., 136*, 106875.

Economics of hydrogen and ammonia energy storage

- **Islanded renewable energy systems with 1000 kW annual average demand**
- **Combined optimal sizing and scheduling to minimize LCOE**
- **NREL data bases for weather/demand**



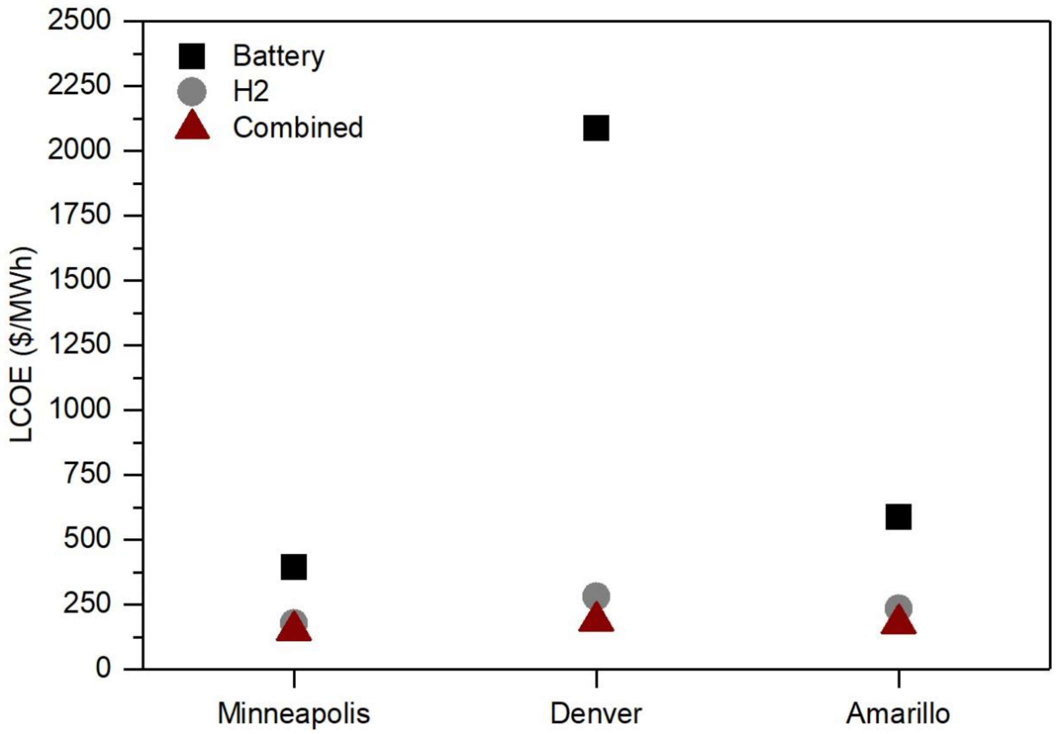


Combining ammonia and hydrogen gives lowest cost in all locations

Hydrogen and Ammonia Renewable Energy Storage Systems

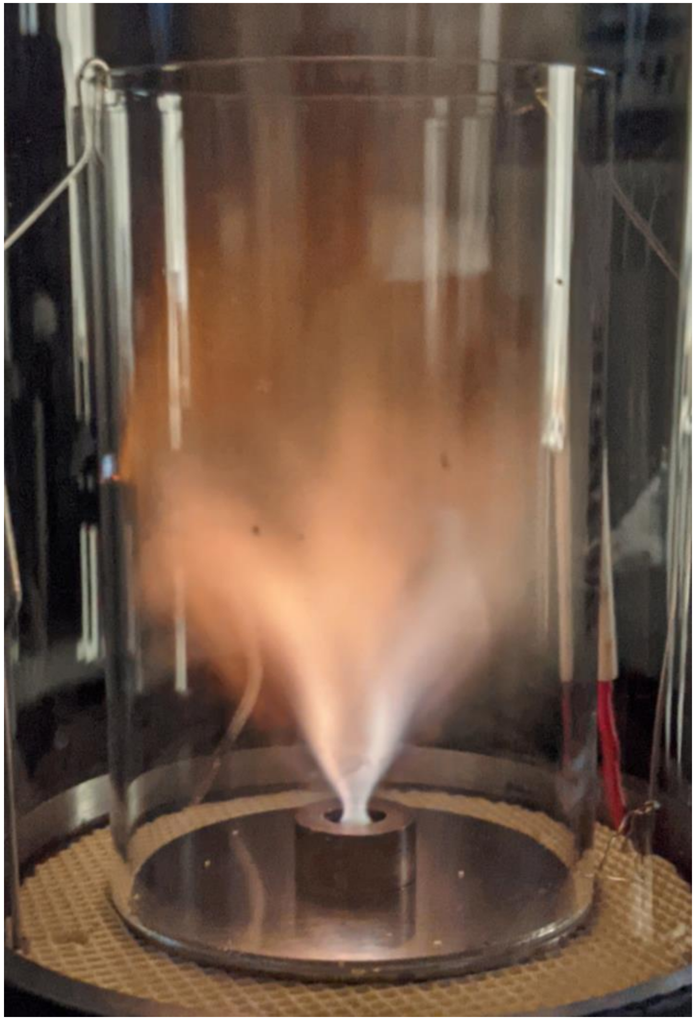
Palys & Daoutidis. (2020). *Comput. Chem. Eng.*, *136*, 106875.

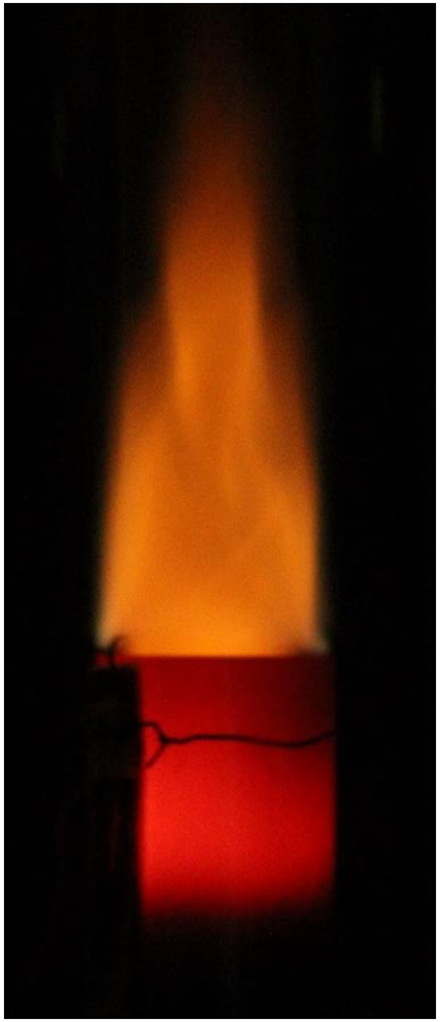
Optimal economics: Levelized cost of energy



- **Batteries alone are expensive (especially for significant long-term storage)**
- **Hydrogen provides improvement**
- **Hydrogen *and* ammonia is optimal –** Hydrogen is better short-term storage but, ammonia is better long-term storage as it is significantly less costly to store

NH_3 Burner studies





- Swirl-stabilized burners
- H_2/NH_3/Air
- 80-98% ammonia by energy
- $N_2O + NH_3$ emissions undetectable $\leq$1 ppm
- Concept scales to much larger applications

NH_3 – Fueled Grain Dryer Demonstration

- Successfully tested Oct & Nov 2022
- Scaled burner application
- 245 Bushel Capacity
- 20/80 mix of H_2/NH_3

Tractor fueled by renewable ammonia


(Reese, 2019)

Field tested June 2019

Ammonia-fueled tractor and Semi incorporating a cracker and fuel cell

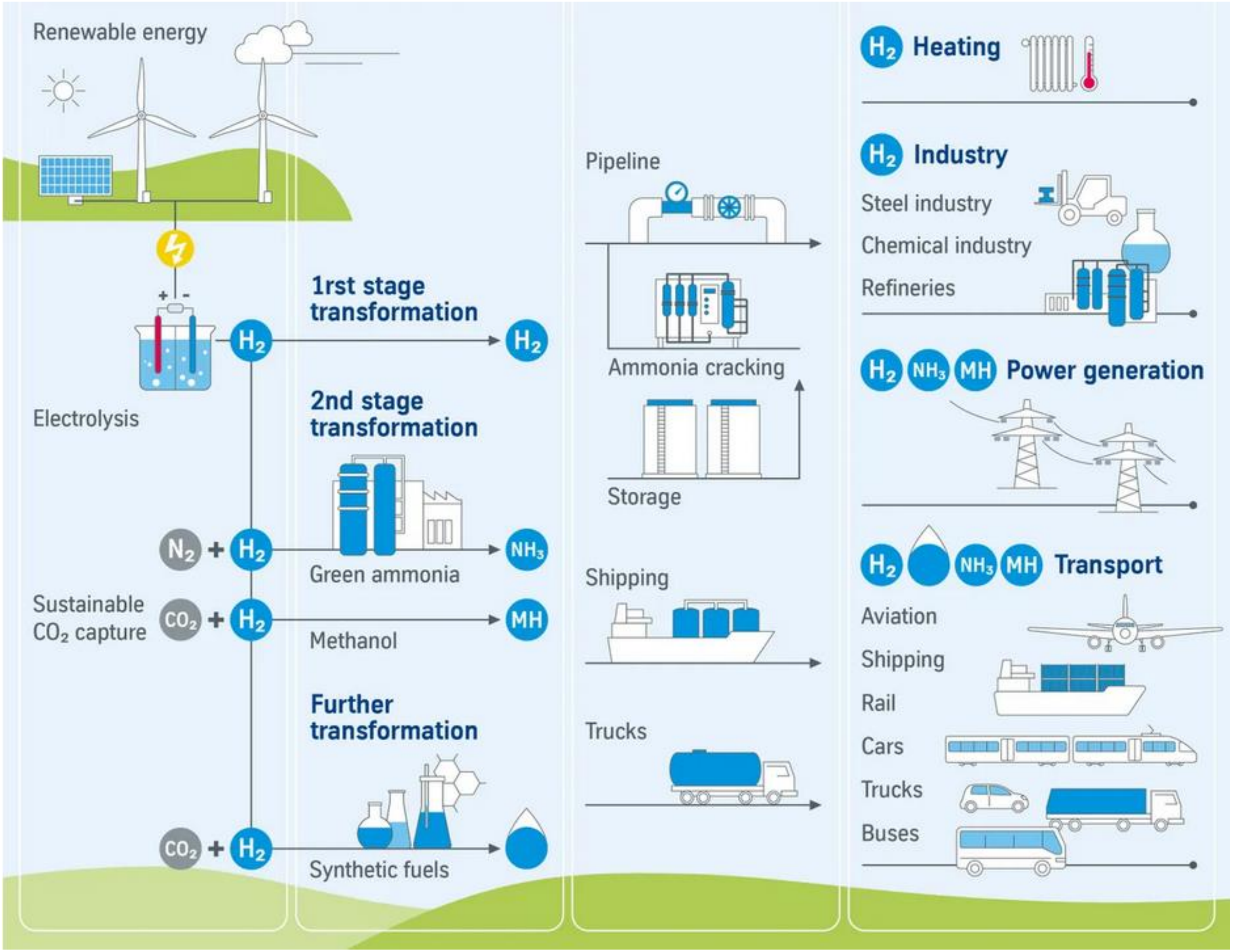
Source: Amogy

Barriers for Farmers and Farm Businesses:

1. Electrolyzer supply
2. Scale – it does matter.
3. Finance
4. Partner mix
5. Storage (anhydrous ammonia vs urea)
6. Experience in this field
7. Pricing / risk management
8. Sophisticated competition

- For farmers, ownership of the fertilizer demand should trump all other competition.

Options for Green H_2 Gases and Fuels:



Credit: Thyssen Krupp

Take Home Green Hydrogen and Ammonia Message:

- The Inflation Reduction Act provides a $3 /kg of hydrogen production incentive with a direct pay option and this has dramatically changed the playing field making production and use economical.

- The University of Minnesota is working to improve the technology. However, green hydrogen and ammonia production systems are commercially available and ready for deployment within the Midwest.

- The question now is "How does the Midwest best position itself to take advantage of this opportunity?"

- Our focus is on agriculture and bringing this technology to Midwest farmers, farm cooperatives, and businesses but there are broad implications for the region.

- Farmer-owned cooperatives could utilize renewable hydrogen for production of anhydrous ammonia, urea, methanol, sustainable aviation fuel, and other molecules.

- Green nitrogen fertilizer is transformative and is a gateway for other green hydrogen energy applications within the Midwest.

WCROC: Driven faculty and staff leading innovation in agriculture and beyond!

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