Green Ammonia for Sustainable Energy and Agriculture

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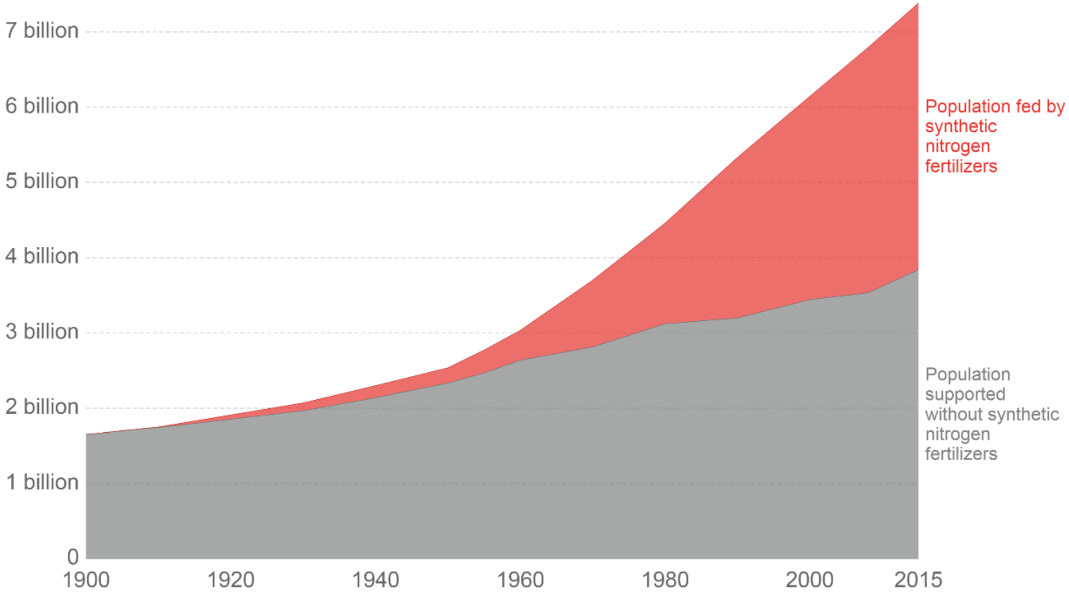
Ammonia: Feeding the World

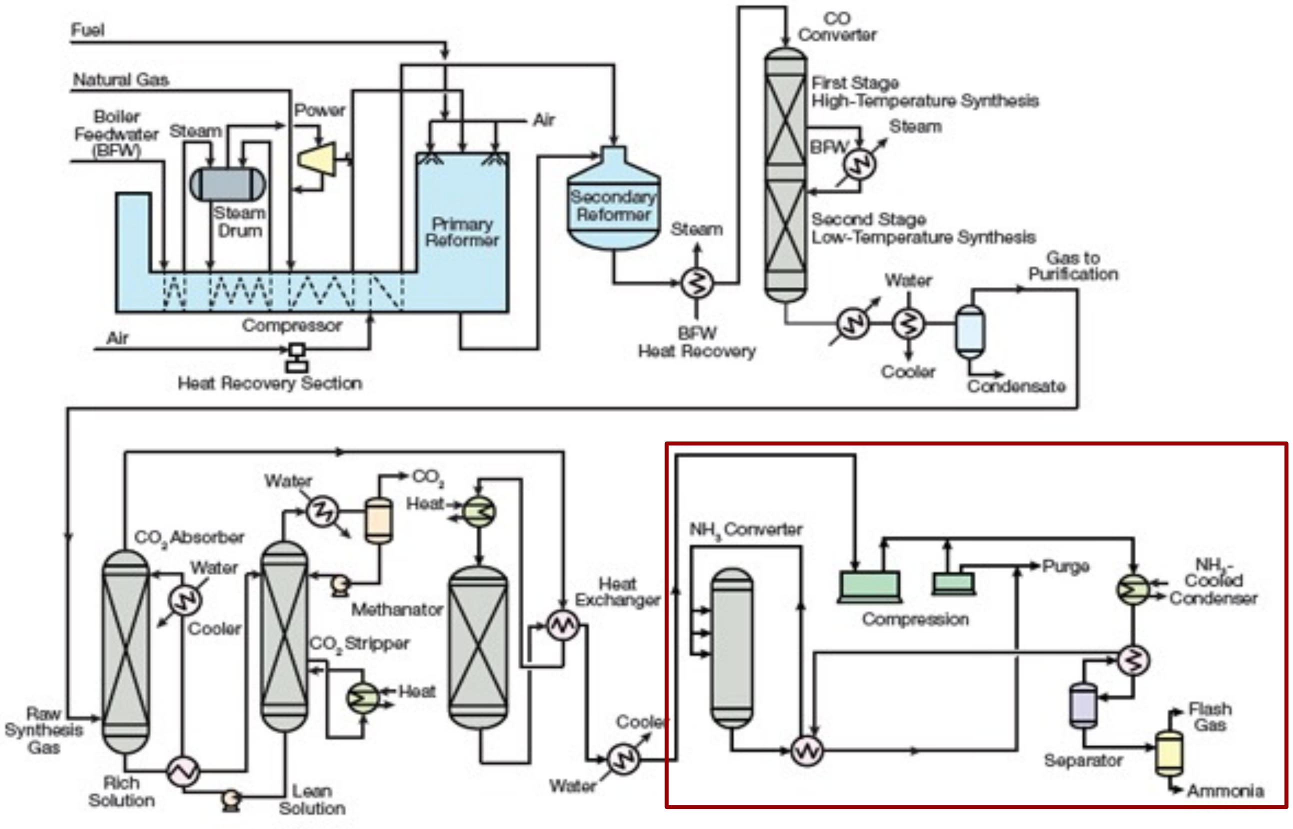
- Backbone of nitrogen fertilizer:
  - Anhydrous ammonia (direct application), urea, ammonium nitrate, UAN, …
  - Massive production scale (~180M mt/y)
- Feeds half of the global population



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.

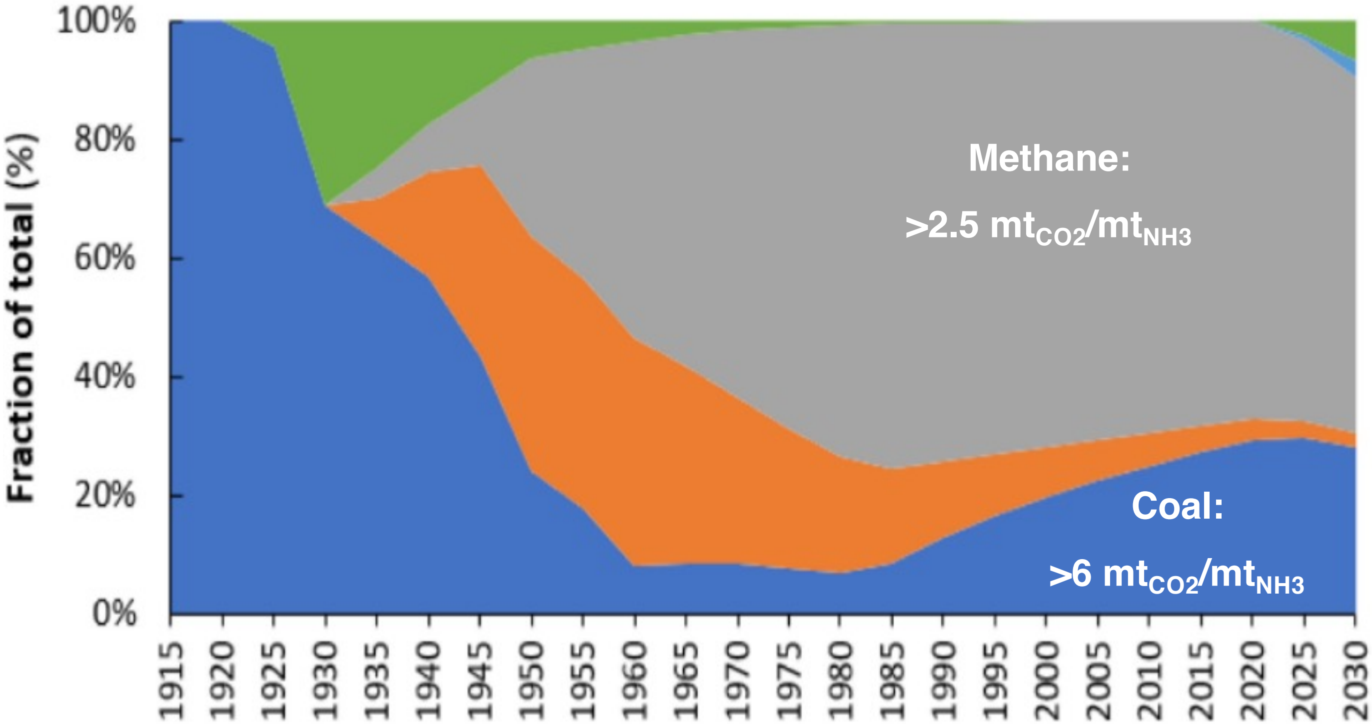
Ammonia Production: Haber-Bosch Process

- Centralized production (~1M mt/y) - transportation
- 80% used for fertilizer



Source: Pattabathula & Richardson, *CEP*, September 2016, 69-75.

Ammonia Production: Hydrogen Source



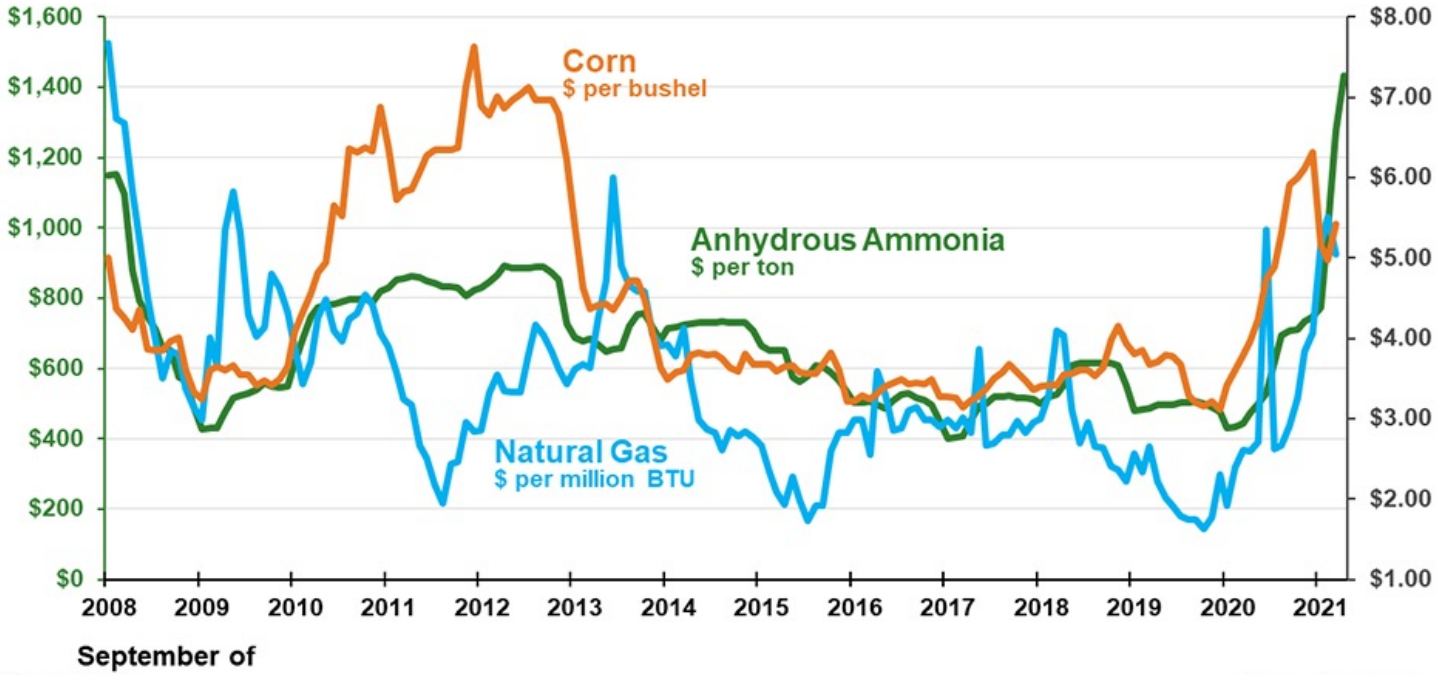
Source: Rouwenhurst et al. (2022), *Sustain. Chem. 3*(2), 149-171.

- 99% from fossil fuels
- 45% global H_2 consumption
- 2% GHG emissions

Need sustainable alternative

Ammonia Farmgate Price (Illinois)

Figure 1. Anhydrous Ammonia, Henry Hub Natural Gas Price, and Corn Prices



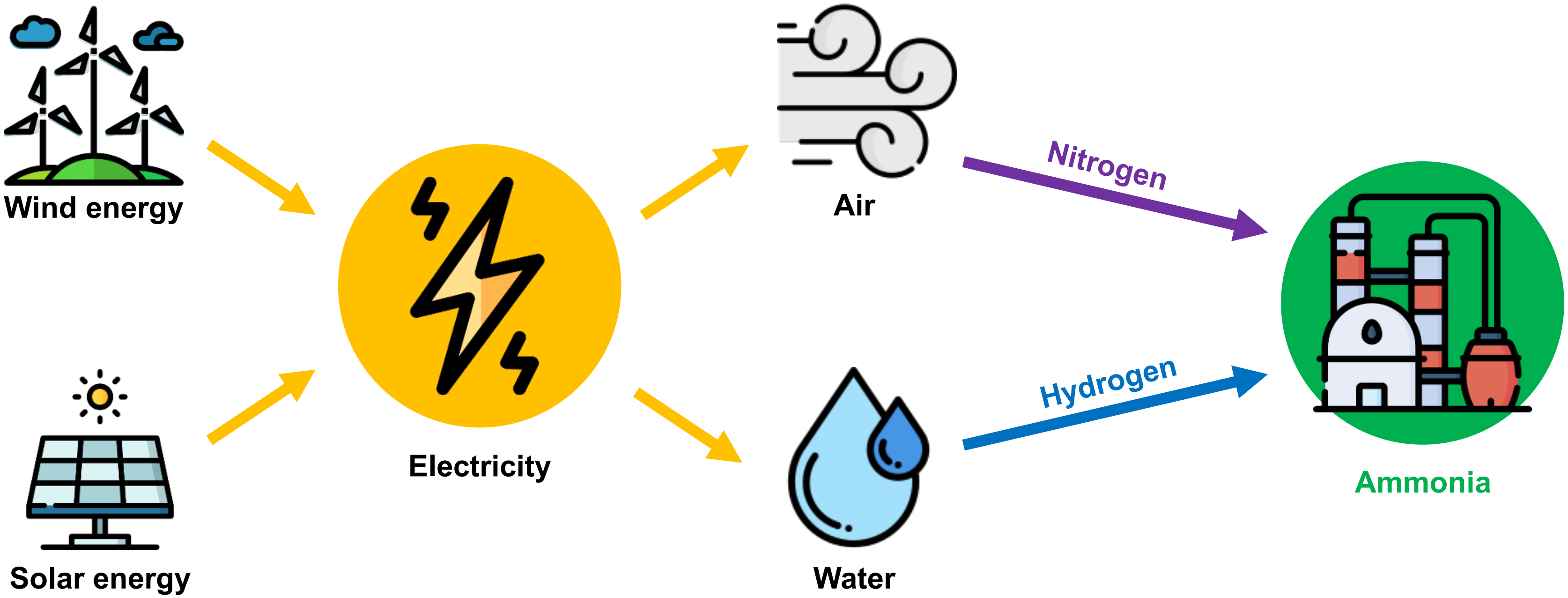
ILLINOIS

Source: USDA and Energy Information Agency

farmdocDAILY

- Price depends on natural gas prices, food prices, global conflict,…
- Dominant variable operating cost for crop farmers
- Price stability key concern

Renewable (Green) Ammonia



- Current demonstration facilities: ~10,000x smaller
- Decreasing renewable electricity cost, policy (IRA) → significant corporate, government interest

Green Ammonia – Development Projects

CF Industries and LOTTE CHEMICAL Corporation to explore joint clean ammonia production

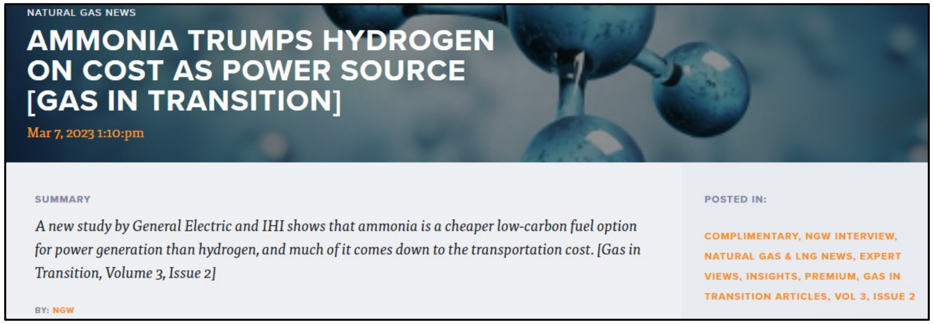
Published by Emily Thomas, Deputy Editor
World Fertilizer, Thursday, 02 March 2023 11:04

Maire Tecnimont Group (MT.MI) Reaches an Agreement With Greenfield Nitrogen LLC for the Development of a Green Ammonia Plant in the United States

NEWS PROVIDED BY
Maire Tecnimont S.p.A. →
Sep 28, 2021, 11:57 ET

Air Products partners on $5-billion green ammonia, hydrogen project in Saudi Arabia

13:00 PM | July 7, 2020 | Mark Thomas


NATURAL GAS NEWS

AMMONIA TRUMPS HYDROGEN ON COST AS POWER SOURCE [GAS IN TRANSITION]

Mar 7, 2023 1:10:pm

SUMMARY

A new study by General Electric and IHI shows that ammonia is a cheaper low-carbon fuel option for power generation than hydrogen, and much of it comes down to the transportation cost. [Gas in Transition, Volume 3, Issue 2]

BY: NGW

POSTED IN:
COMPLIMENTARY, NGW INTERVIEW, NATURAL GAS & LNG NEWS, EXPERT VIEWS, INSIGHTS, PREMIUM, GAS IN TRANSITION ARTICLES, VOL 3, ISSUE 2


Wednesday, 18 January 2023

GE and Japan's IHI to develop 100% ammonia-capable combustion

GE Gas Power and Japan's IHI Corp have teamed up to develop gas turbines capable to fully run on ammonia by 2030. "We want to satisfy demand for large-scale ammonia gas turbines (…) and expand the fuel ammonia value chain," said IHI president Hiroshi Ide whose company is fast-tracking a demo project at JERA's Hekinan thermal power unit 4.

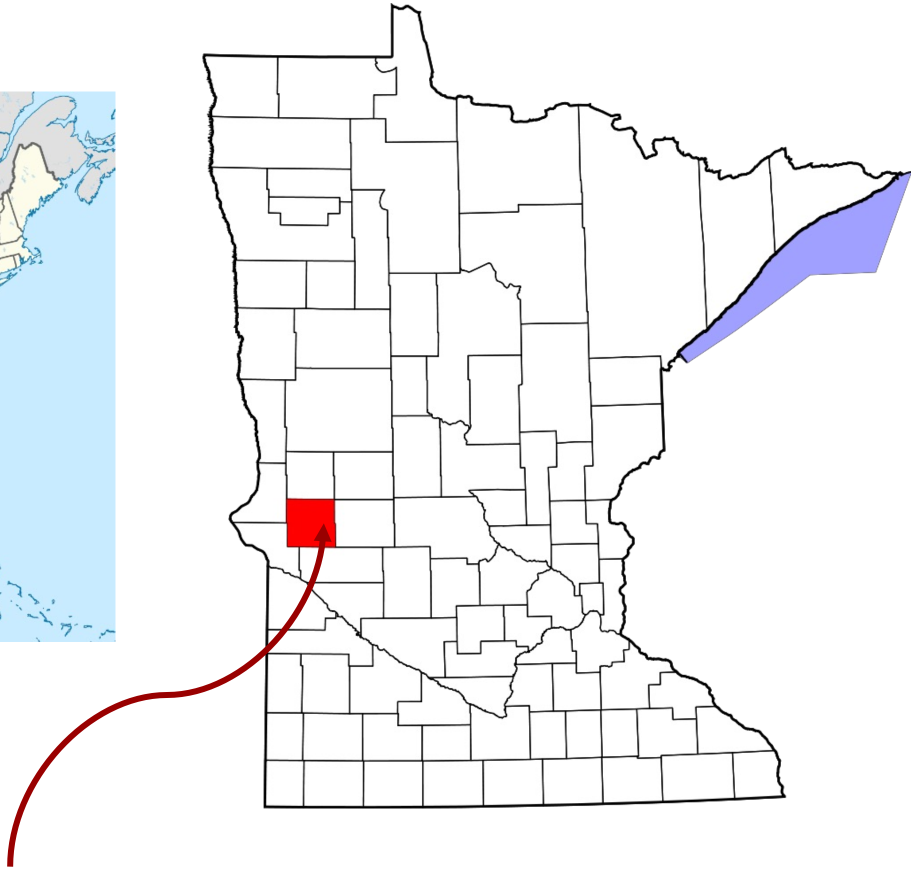
Brooge Energy, Siemens Energy Partner For Solar & Green Hydrogen in UAE

By Saur News Bureau / Updated On Thu, Feb 16th, 2023

Highlights :

- Brooge Renewable Energy and Siemens Energy will build up to 650 MW solar PV plant to supply planned Phase 1 of the green ammonia project with renewable energy that belongs to Brooge.
- Siemens Energy will serve as the technical partner to Brooge and exclusive provider of solutions.

Morris, Minnesota



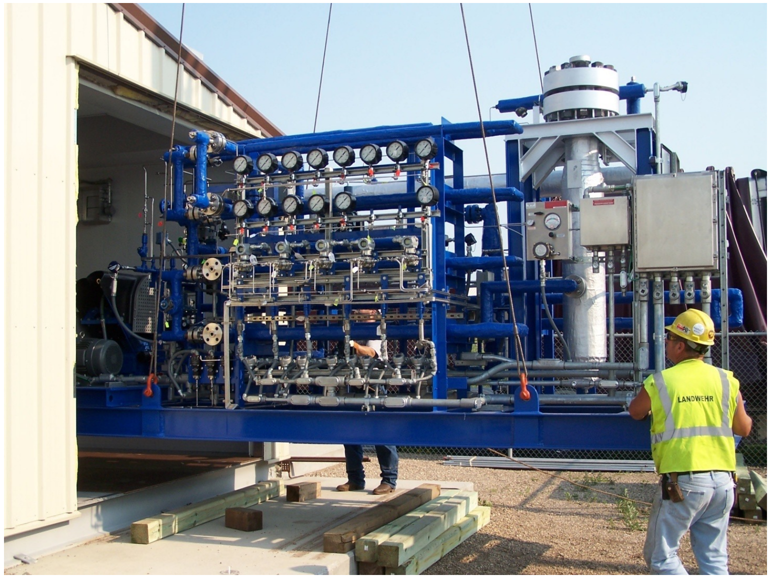
Morris, Minnesota

Wind to Ammonia at Morris

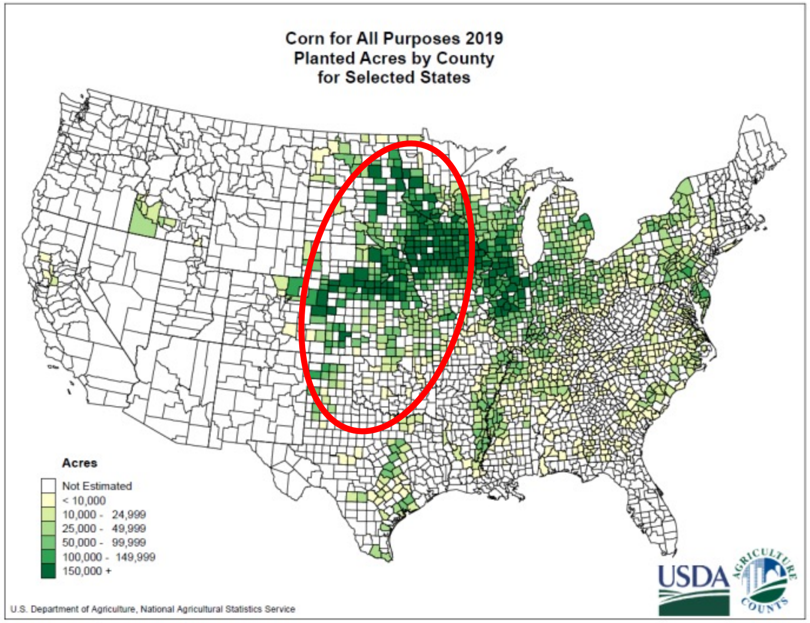
- Scaling down Haber-Bosch to match wind
- Ammonia as fertilizer

Small-scale Renewable Haber-Bosch

- Installed in 2013 - first of its kind!
- Uses ~10% of 1.65MW wind turbine
- Fabricated by Sep-Pro Systems, Houston, TX
- Produces 80 kg/day (26.3 ton/year)
- Capital cost: 1.5 MM$ (synthesis), 2.6 MM$ total
- Synthesis consumes ~2.12 kWh/kgNH_3

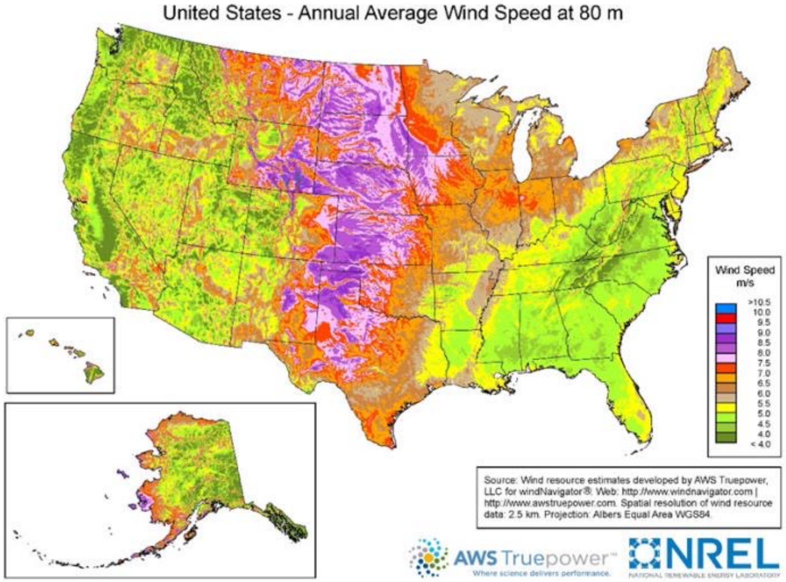


Distributed Production of Green Ammonia



Corn for All Purposes 2019
Planted Acres by County
for Selected States

U.S. Department of Agriculture, National Agricultural Statistics Service



United States - Annual Average Wind Speed at 80 m

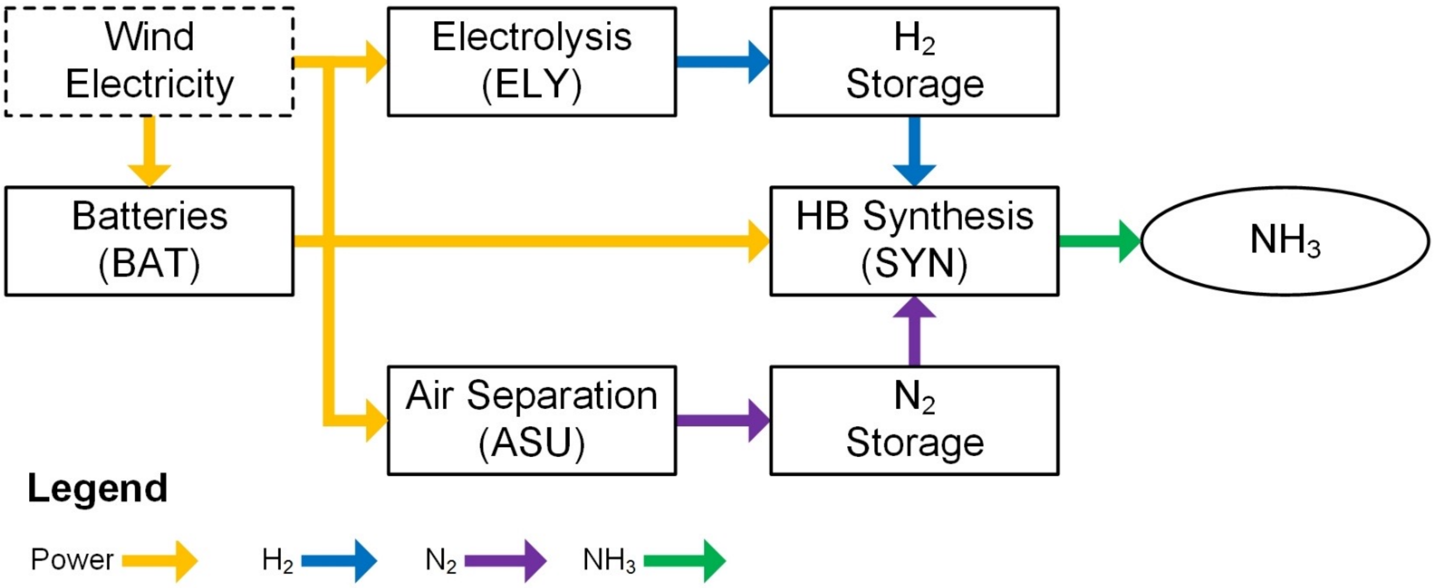
Source: Wind resource estimates developed by AWS Truepower, LLC for windNavigator®. Web: http://www.windnavigator.com | http://www.awstruepower.com. Spatial resolution of wind resource data: 2.5 km. Projection: Albers Equal Area WGS84.

- US wind resource synergistic with Midwest corn production and nitrogen fertilizer demand
- Opportunity to utilize “stranded” wind and solar resources (and excess nuclear)
- Distributed production meaningful but costly
- Economics crucial for process design and deployment

Renewable Ammonia System Design

Wind energy ("feedstock") is intermittent

- Need for storage: Batteries/H_2/N_2
- Time-varying (rather than steady-state) chemical production



How do we design and size such a system ?

(location / intermittency, electricity price, scale)

Renewable Ammonia System Design

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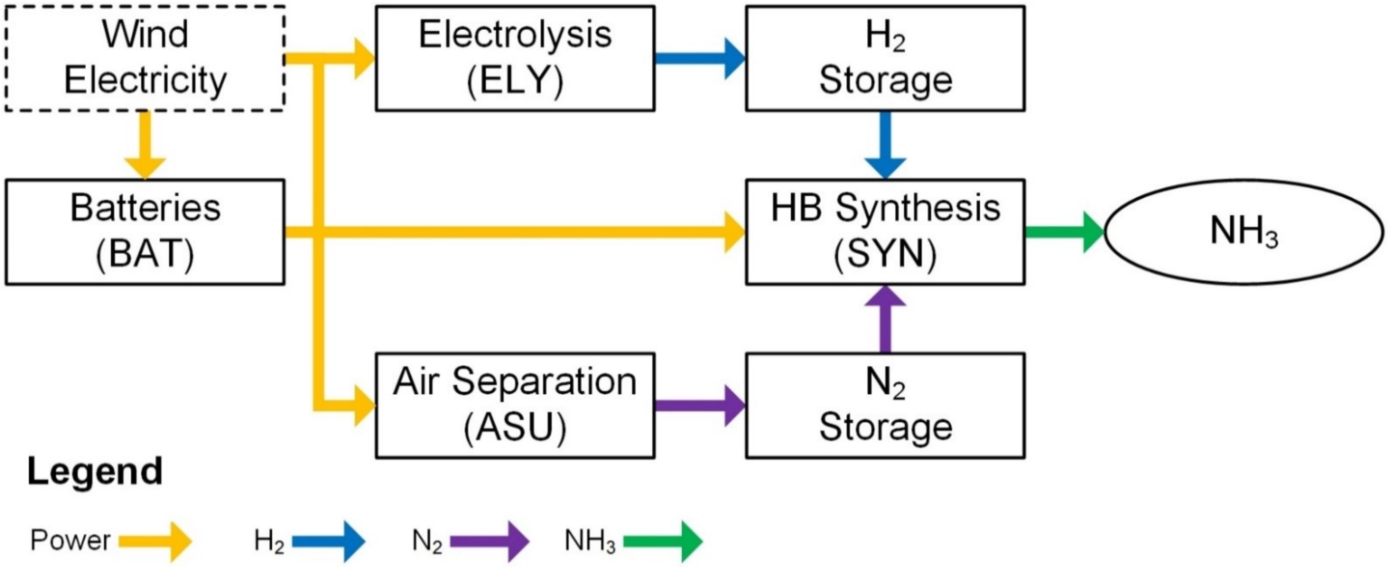
- Time-varying (rather than steady-state) chemical production

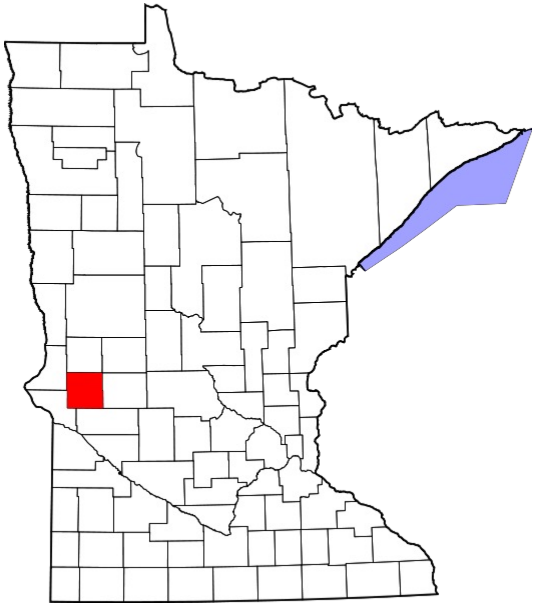


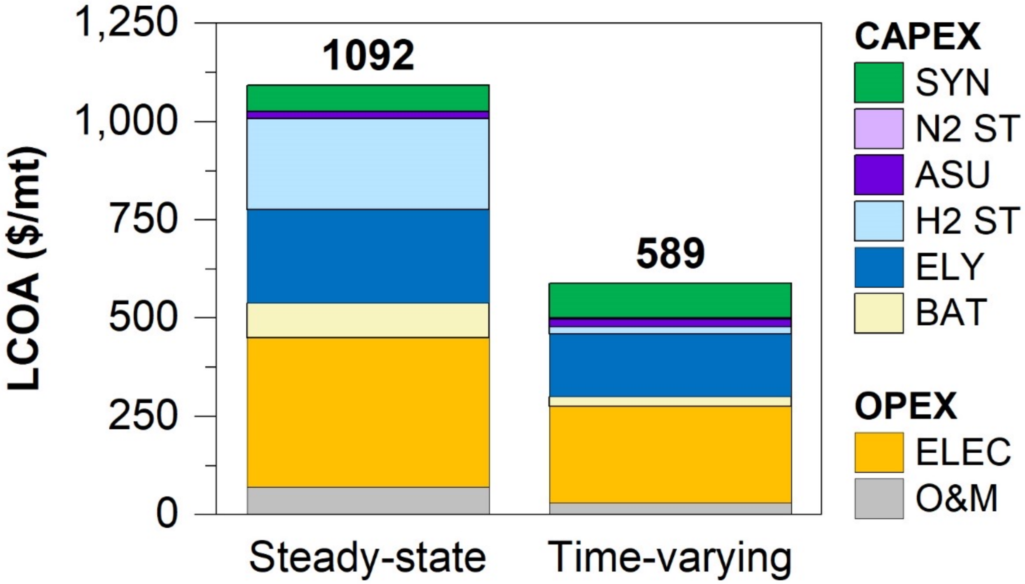
Combined design and scheduling

- Fixed annual production capacity
- Size each unit to minimize levelized cost of ammonia
- Hourly scheduling simultaneously

[1] Palys and Daoutidis (2020). *Comput. Chem. Eng. 136*, 106785.

The Case for Time-varying Ammonia Production





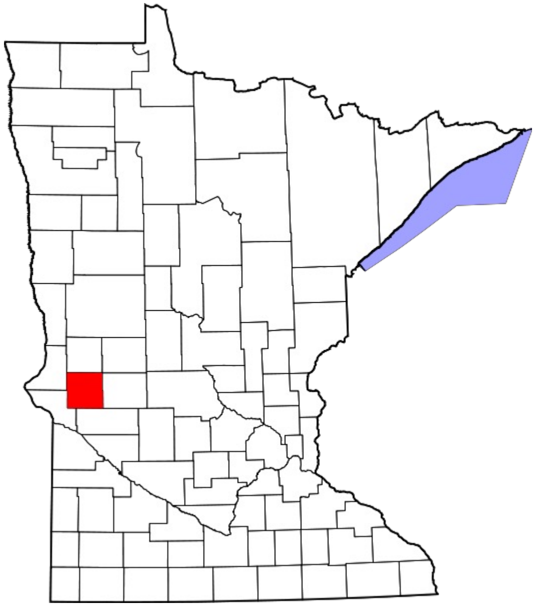
- Wind capacity factor: 42%
- PPA @ $25/MWh
- Electrolysis CAPEX: $900/kW
- 50,000 mt/y production scale

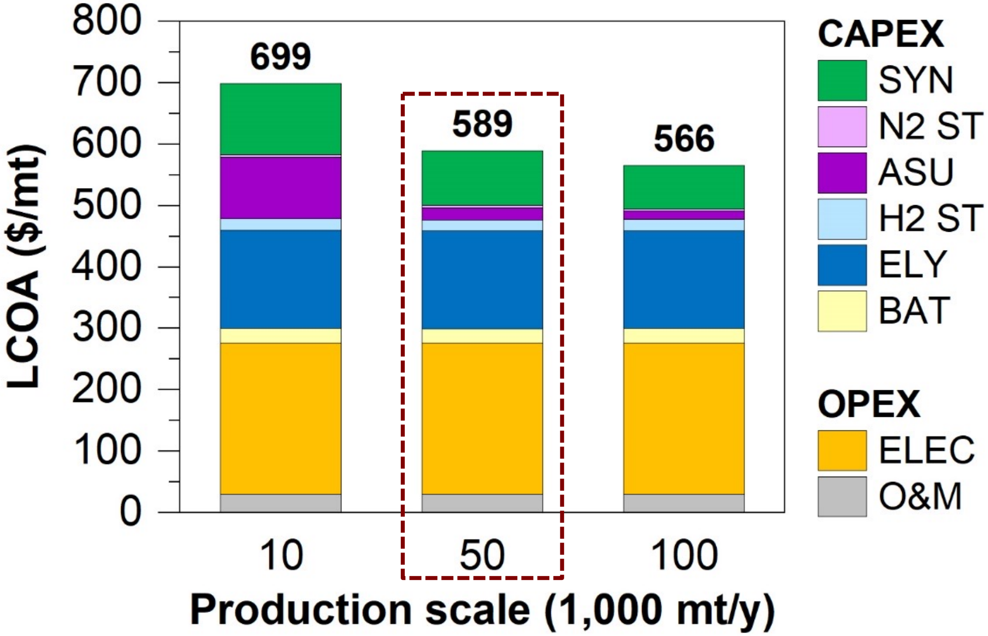
Facility with time-varying production

- Synthesis oversized by 70%
- 35% lower energy costs
- 90% less H_2 storage

45% lower LCOA!

Renewable Ammonia Economics: Stevens County, MN





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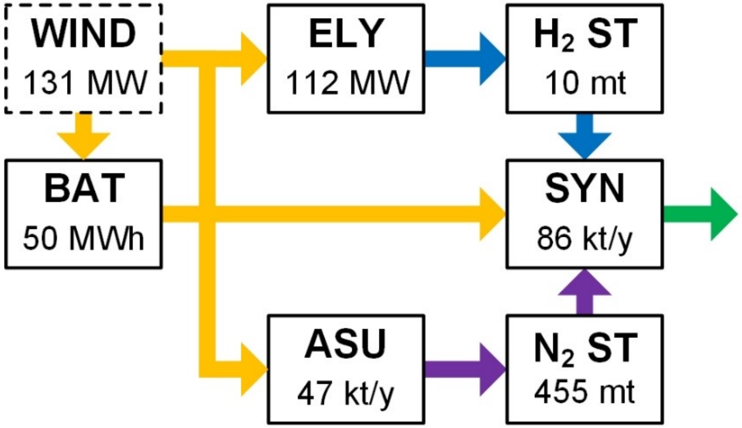
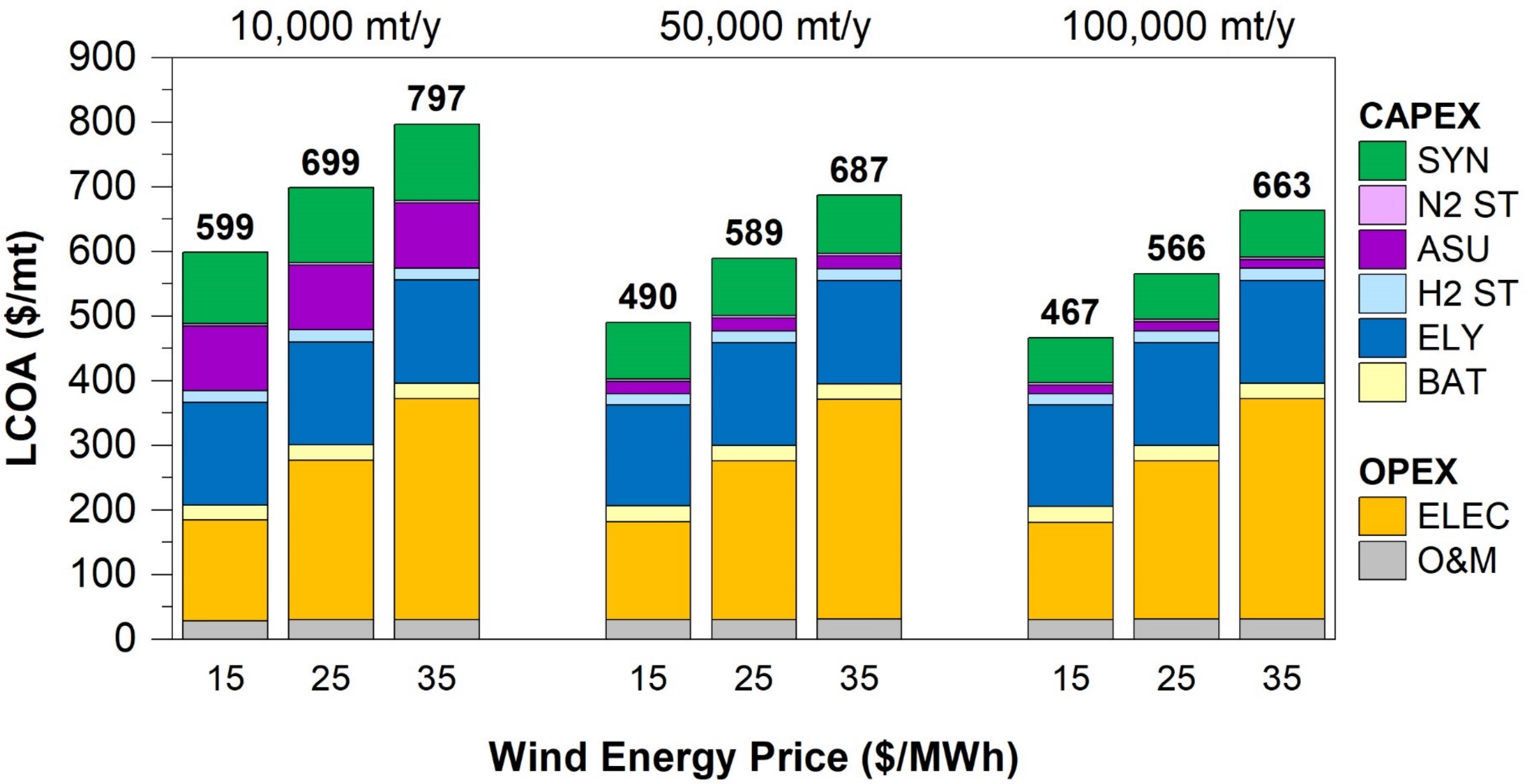


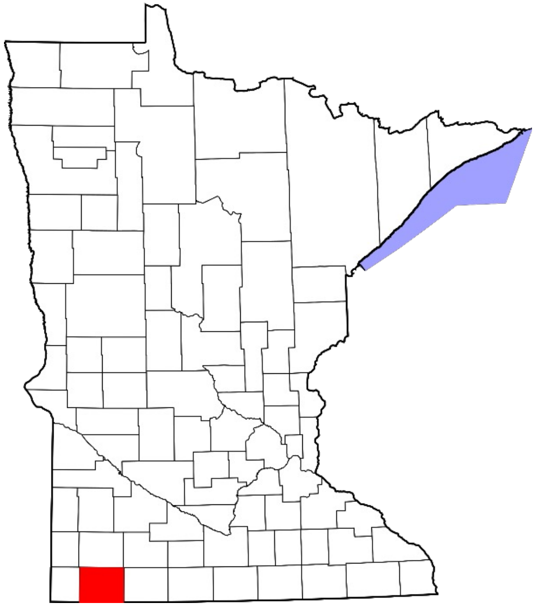
Scale matters (synthesis, ASU) !

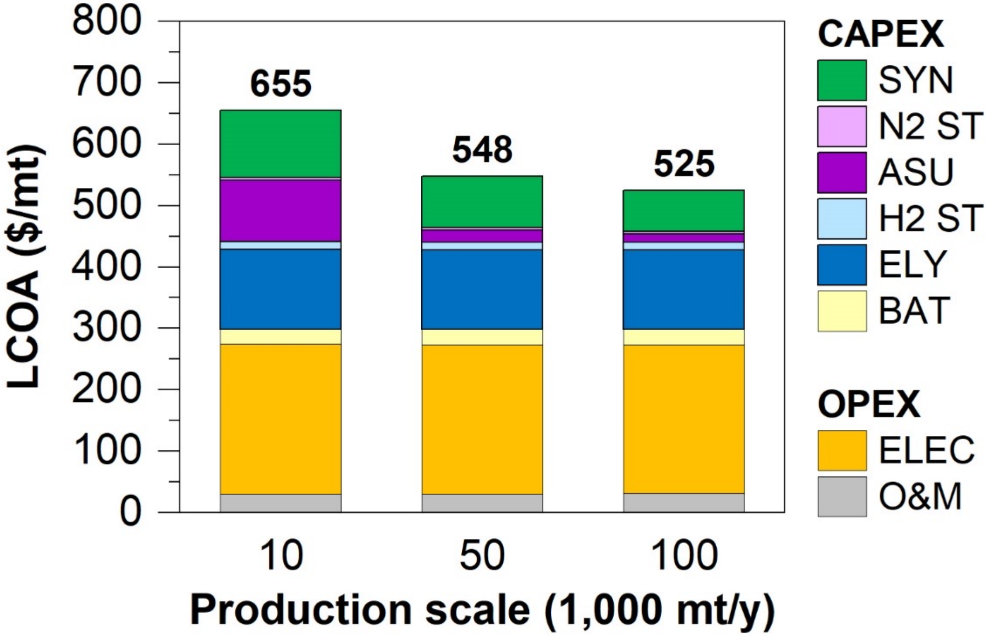
Renewable Ammonia Economics: Stevens County, MN



Electricity price impact is significant: Δ$10/MWh → Δ$100/mt

Renewable Ammonia Economics: Nobles County, MN





- Wind capacity factor: 51%

~$40/mt less than Stevens County

- PPA @ $25/MWh
- Electrolysis CAPEX: $900/kW

Electricity price > Scale (small) > Location

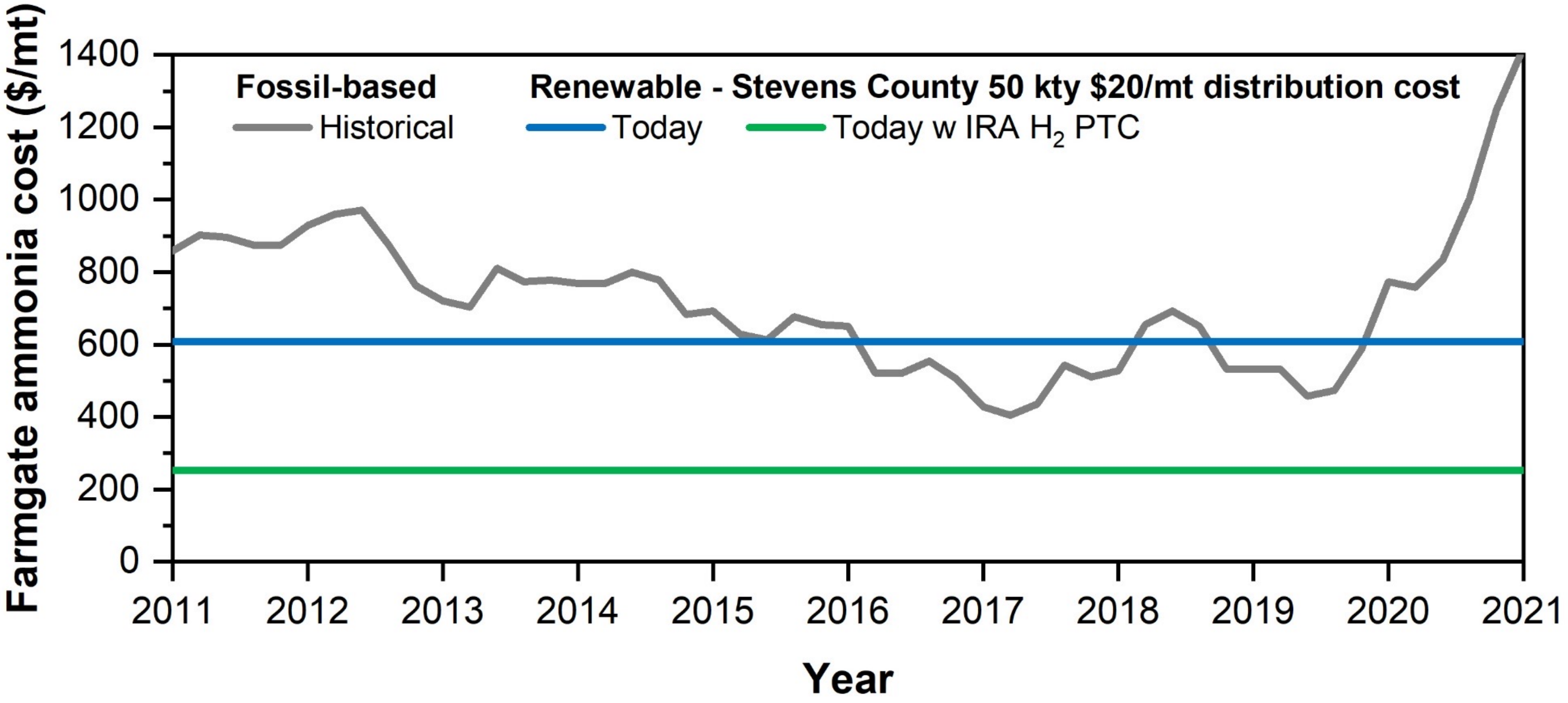
IRA H_2 Production Tax Credit is Transformative

IRA: \$3/kg H_2 credit for CI<0.45 kg_{CO2}/kg_{H2}

- \$529/mt ammonia for first 10 years of production
- \$356/mt ammonia levelized over 20 year project

Wind-to-NH_3

- 42% CF
- PPA @ \$25/MWh

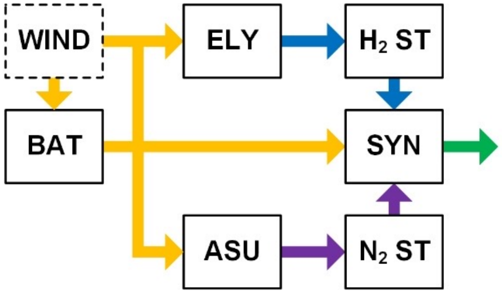


Renewable Ammonia Deployment

Palys et al. (2019). *Ind. Eng. Chem. Res. 58 (15)*, 5898-5908.

Scale and location?

Account for spatial variation in wind availability

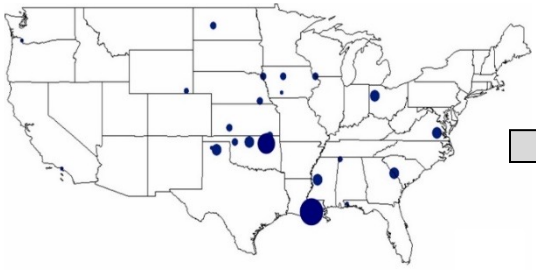


Renewable production facilities

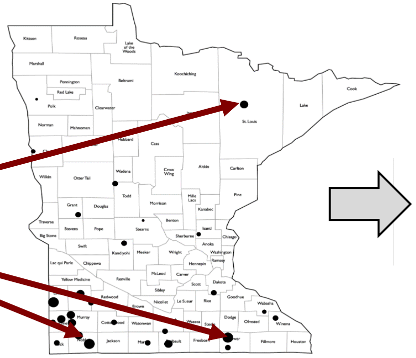
?

How much ammonia from each producer?

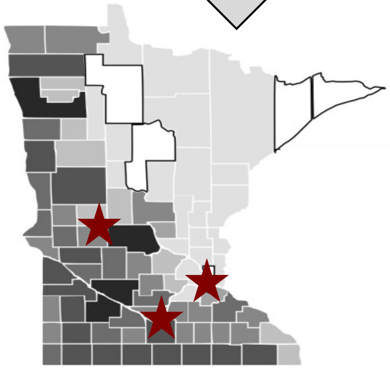
Existing conventional producers



Transportation



Candidate renewable production sites



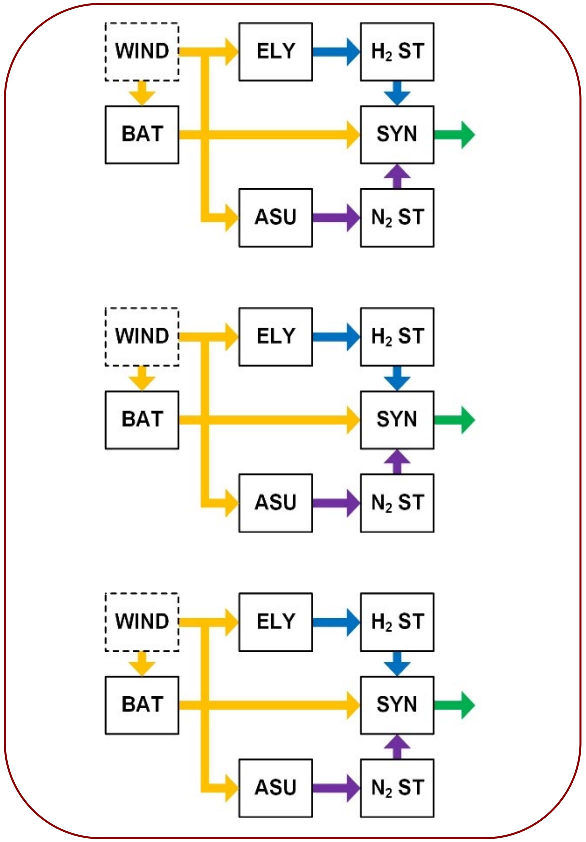
Distribution to local demand

Which distribution centers?

Modular Manufacturing and Deployment

Palys et al. (2019). *Ind. Eng. Chem. Res. 58 (15)*, 5898-5908.

- Manufacture systems of same size, then deploy
- Efficiency through standardization

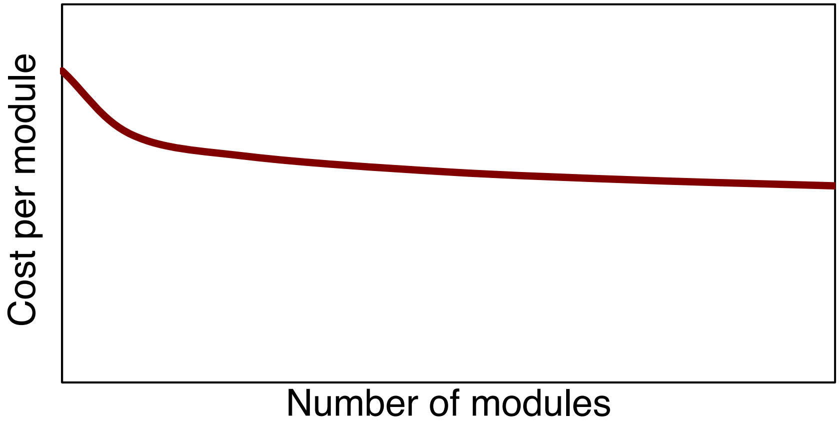


$$C = c_m n_m^{0.9}$$

C – **total capital cost**

c_m – **single module cost**

n_m – **number of modules installed**



Economies of volume *instead* of economies of scale

Supply Chain Optimization

Palys et al. (2019). *Ind. Eng. Chem. Res. 58 (15)*, 5898-5908.

Minimize:

Total supply chain cost = Conventional purchase costs
+ Transportation costs
+ Capital and operating costs of new renewable plants

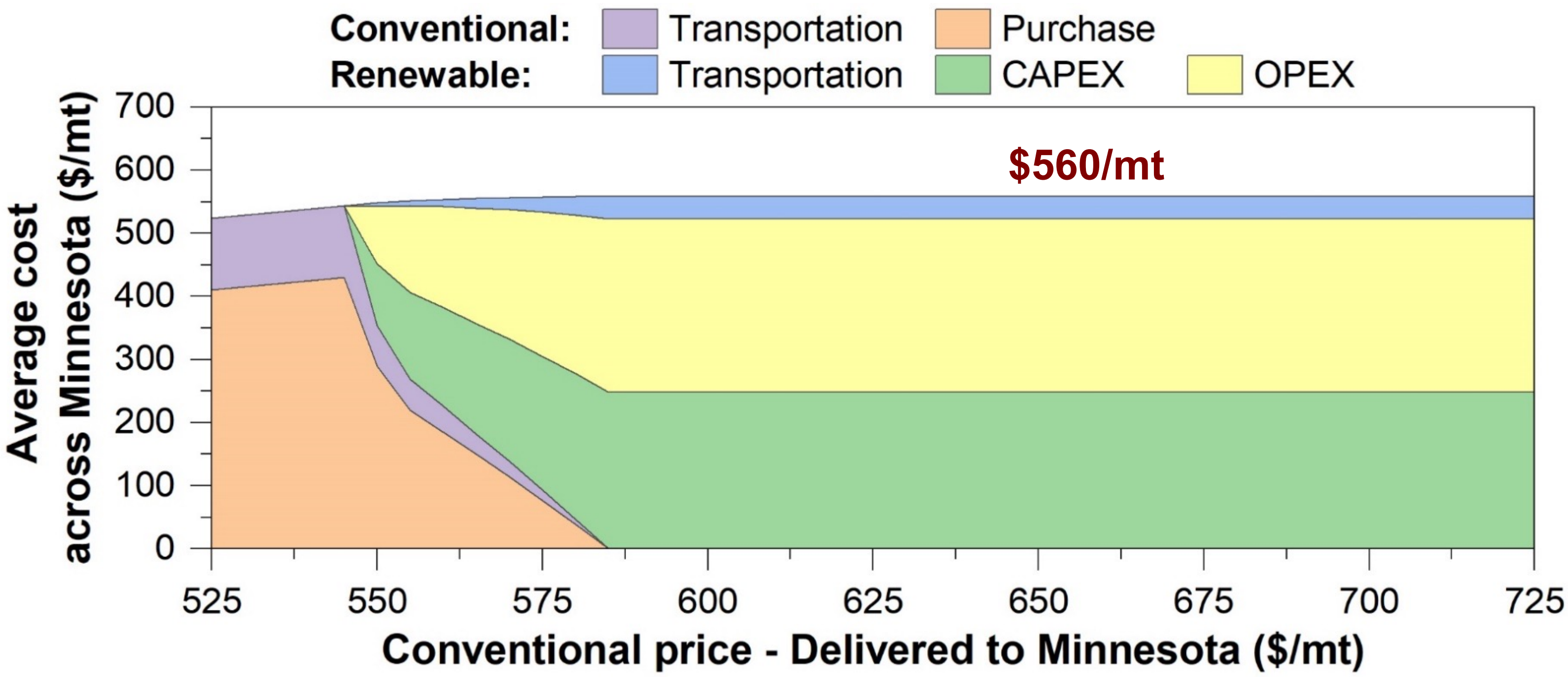
Decisions:

- From which producer and how much conventional ammonia to buy
- How to distribute ammonia
- Where and how many renewable production modules to install

Constraints:

- Ammonia mass balances at distribution and demand sites
- Conventional purchase limits
- Maximum renewable power availability (site-specific)

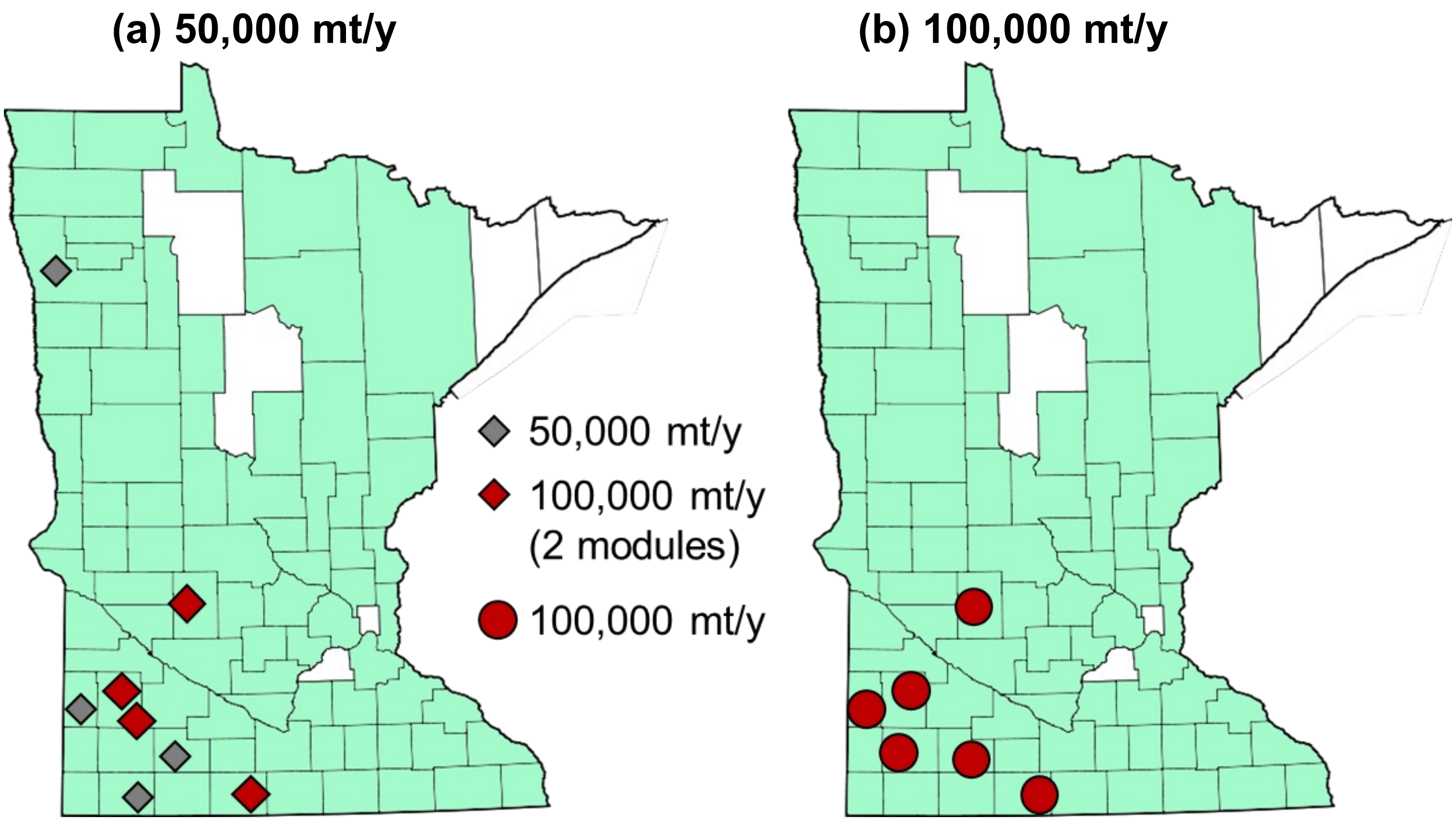
Supply Chain Economics: 50,000 mt/y Modules



Conventional ammonia price in Minnesota:

- Below $550/mt → Business-as-usual
- $550/mt to $585/mt → Renewable ammonia becomes competitive
- Above $585/mt → 100% Renewable, $560/mt stable supply cost!

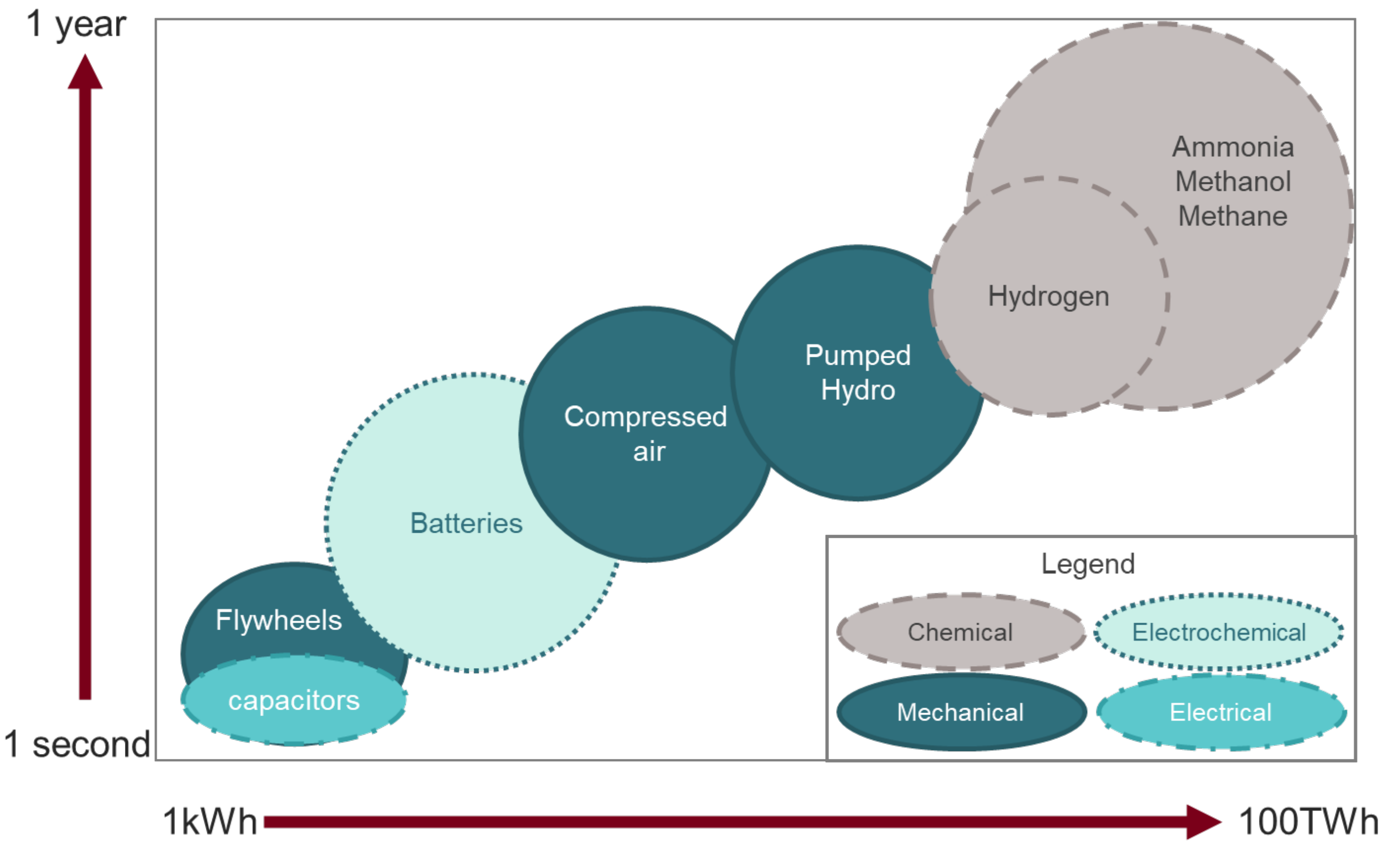
Module Locations at 100% Renewable Supply



- $560/mt vs. $555/mt stable average ammonia cost
- Production scale in 50,000 mt/y to 100,000 mt/y range

Ammonia for Energy Storage

Storage capacity and duration for energy storage technologies



Storage Cost: Hydrogen vs. Ammonia

Hydrogen

- Gas in high pressure vessel: 200 bar to 700 bar
- CAPEX[1,2]: $1,000/kg → $20/kWh

- Salt cavern (geographically limited)[1,2]: $100/kg → $2/kWh

Ammonia

- Liquid at ambient temperature, 10 bar
- CAPEX[1,2]: $5/kg → $0.2/kWh

10 to 100x lower storage cost than hydrogen

[1] Cesaro et al. (2021). *Appl. Energy 282*, 116009.
[2] Fasihi et al. (2021). *Appl. Energy 294*, 116170.

Ammonia storage - CF Industries Glenwood Terminal

- Capacity of 60,000 tons of NH_3
- Equivalent to an estimated 111,000 GWh of electricity
- Currently served by Runestone Electric Association

- >10M mt storage globally, not a theoretical concept

Ammonia as a Carbon-free Fuel

Combustion: Turbines or Engine-Generators

- Ammonia-to-power efficiency: 30-45% LHV
- System design and operational challenges (+$)
    - Lower flame speed
    - Corrosion
    - NO_x and N_2O formation
- Can be aided by H_2 combustion promoter co-mixing
- Can be used for heat or combined heat and power (CHP)
- Demonstrated at MW scale

Direct-fed fuel cells

- Higher efficiency than combustion: >60% LHV
- Avoid combustion byproduct GHGs
- Still at lab/bench scale, years from commercialization

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

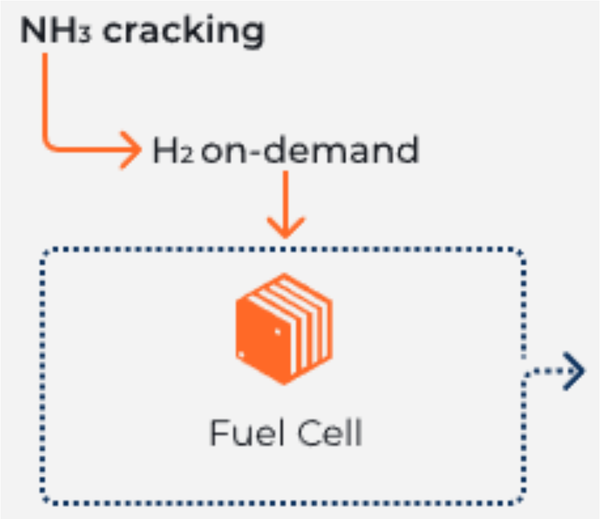
Tractor Fueled by Renewable Ammonia

(Reese, 2019)

Field tested June 2019

Ammonia as a Carbon-free Fuel

- “Cracking” to hydrogen via opposite of synthesis reaction
- Hydrogen-to-power in established fuel cell technology
- Ammonia-to-power efficiency: ~50% LHV
- Demonstrated at 100 kW scale



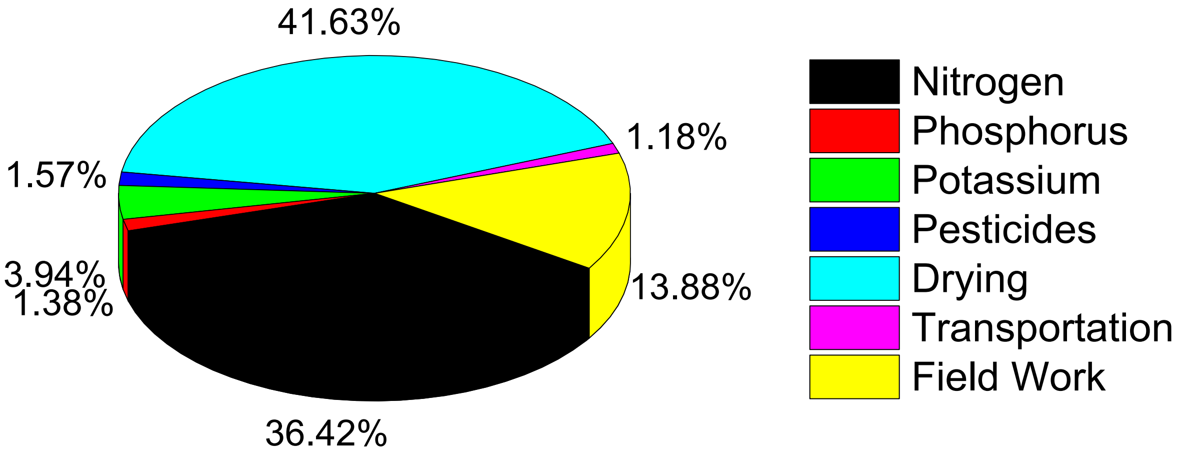
Ammonia-fueled tractor and semi-truck

- Amogy (founded by 4 MIT alumni)
- Cracker and fuel cell
- H_2 on demand
- Commercial transportation

Renewable Ammonia on the Farm

Renewable ammonia utilization:

- Nitrogen fertilizer
- Grain drying fuel
- Tractor fuel
- Energy storage



Potential to reduce conventional corn farming fossil fuel intensity by >90%[1]

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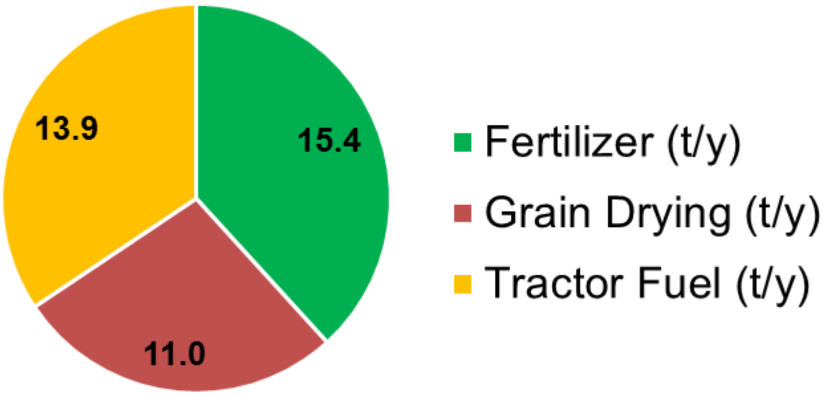
[1] Tallaksen (2017). *Life Cycle Assessment and Cropping Energy Audits for IREE Project RL-0016-13*

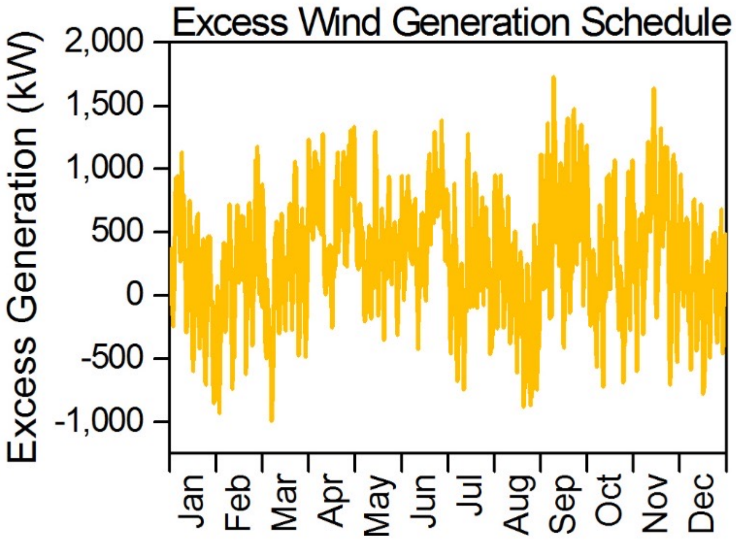
Case Study at Morris, MN

- Two 1.65 MW wind turbines
- Ammonia for farm, approximately 40 mt/y
  - 280 acres corn, 116 acres soy
- Corncob biomass, approximately 196 ton/year[1]
- UMM Campus electrical load: annual average of 950 kWh
- Export power during favorable price signals: Location marginal prices

WCROC Agricultural Ammonia Demands[1]



WCROC-UMM: Generation – Demand



[1] Tallaksen (2017). *Life Cycle Assessment and Cropping Energy Audits for IREE Project RL-0016-13*

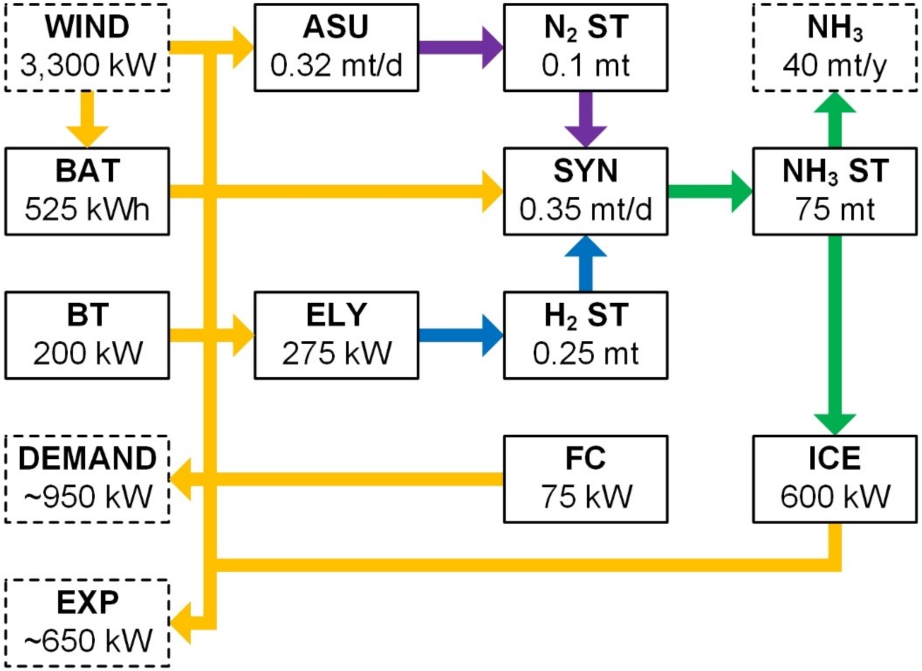
Case Study at Morris, MN

NPC[1]: **\$123,000/y**

CAPEX: \$3.50 MM

OPEX: -\$190,000/y

- Power sale revenue
- Replace fertilizer import
- Replace fuel import



Emissions avoided: **4,325 $mtCO_2$/y**

- Fertilizer production
- Fuels
- Replaced power generation

Emissions Avoidance:
~\$25/$mtCO_2$

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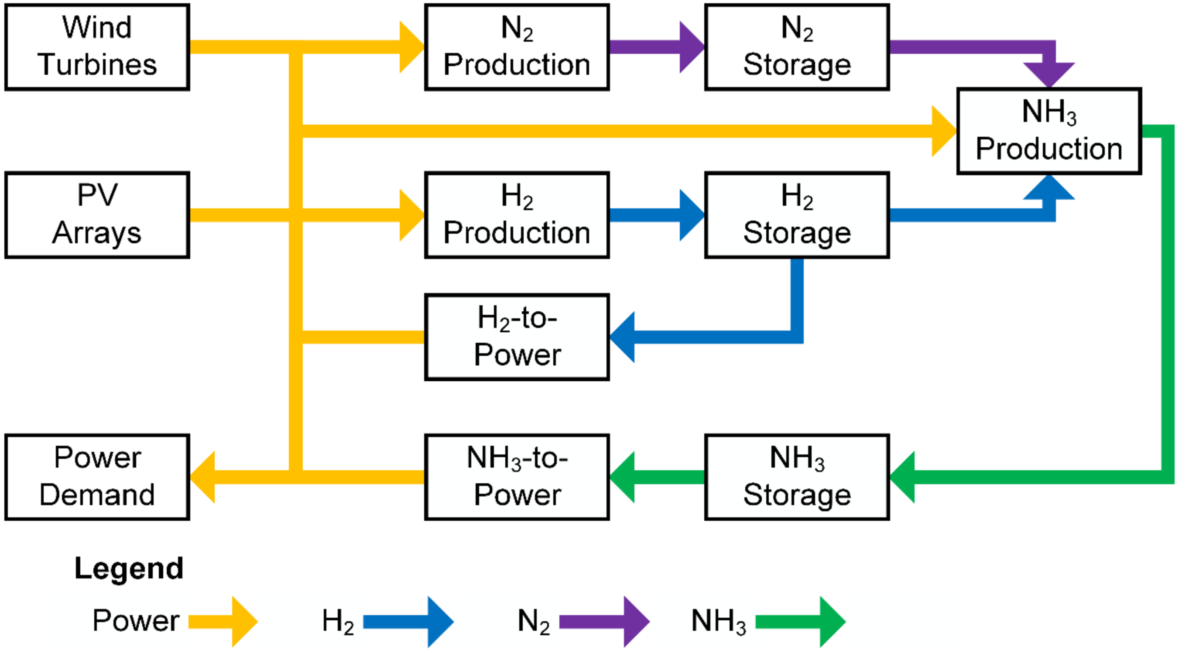
[1] 25 years @ 10% discount rate

Renewable Energy Storage

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

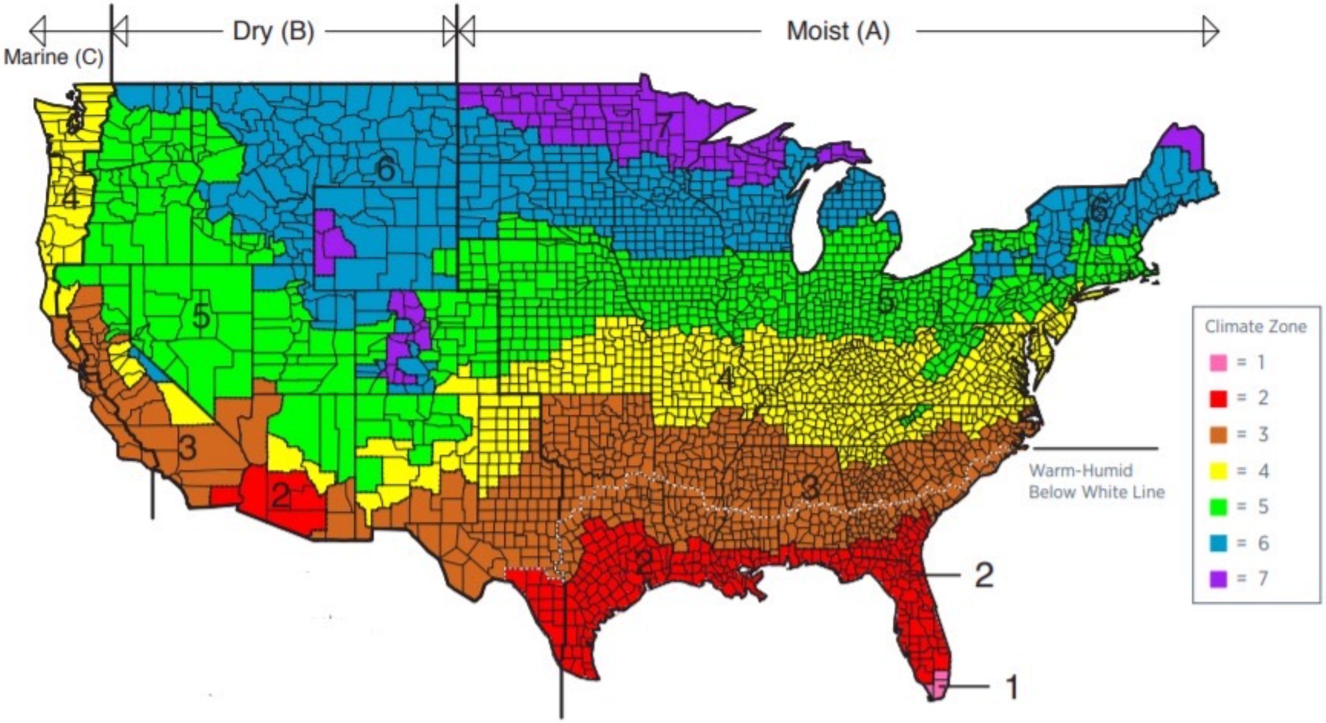


- 100% renewable energy for 1 MW annual average demand
- Hydrogen and ammonia energy storage pathways

H_2-NH_3 Energy Storage Analysis

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

- 15 locations across United States to capture all climate-moisture zones
- Hourly time series data for renewable availability and demand data[1]



Source: PNNL and ONNL. (2010). *Guide to Determining Climate Regions by County.*

1: Miami
2: Houston
3: Phoenix
4: Atlanta
5: Los Angeles
6: Las Vegas
7: San Francisco
8: Baltimore
9: Albuquerque
10: Seattle
11: Chicago
12: Denver
13: Minneapolis
14: Helena
15: Duluth

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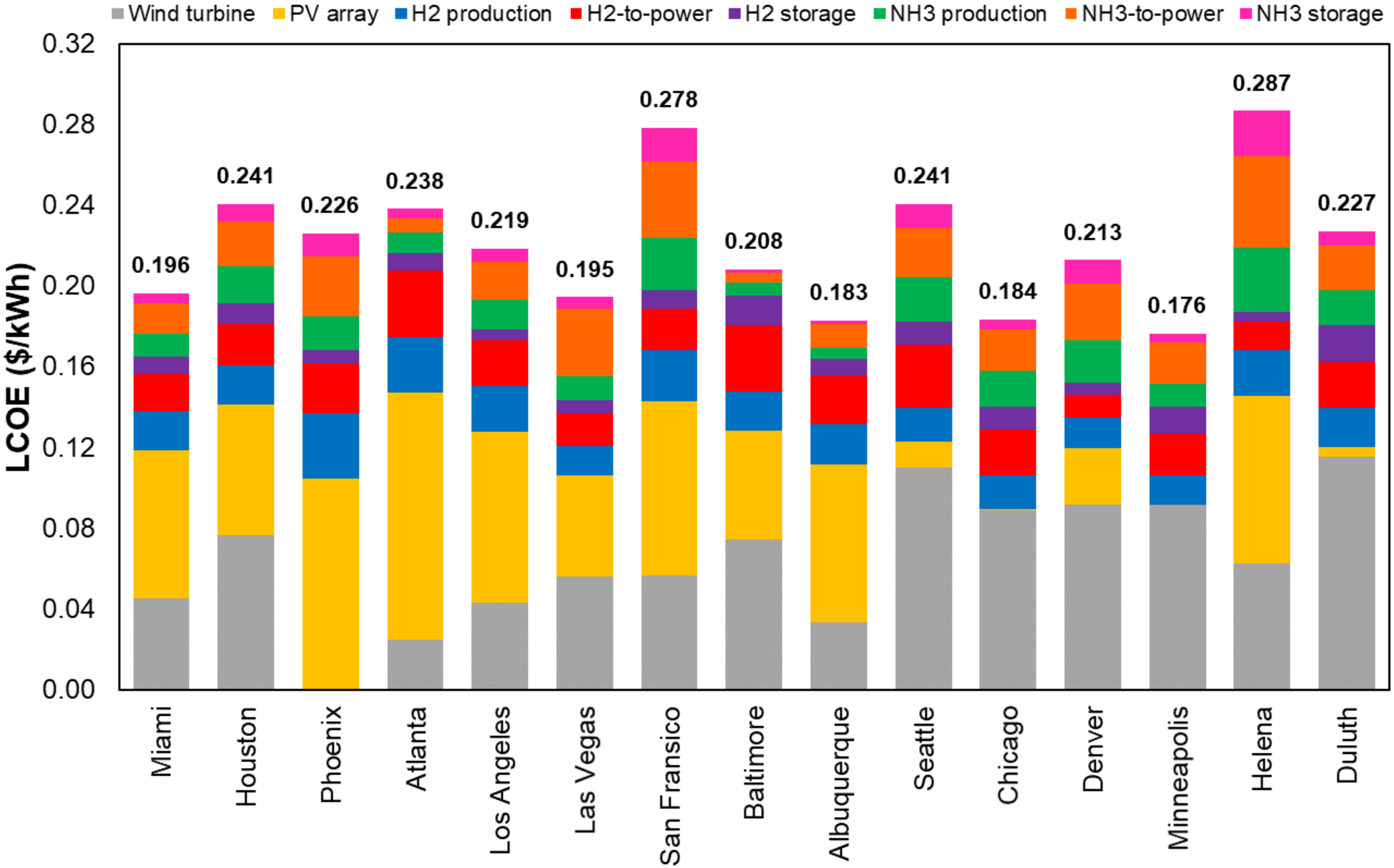
[1] NREL. (2019). National Solar Radiation Data Base, 1991-2005 Update: Typical Meteorological Year 3.

Optimal Economics

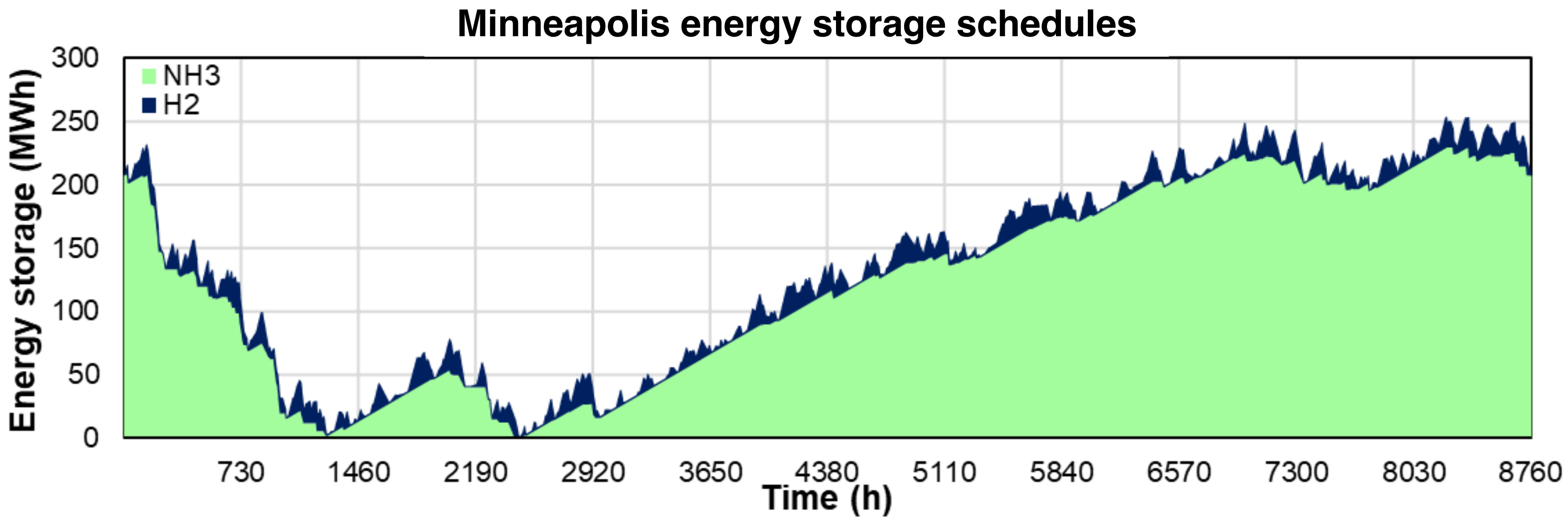
Palys & Daoutidis. (2020). *Comput. Chem. Eng., 136*, 106875.

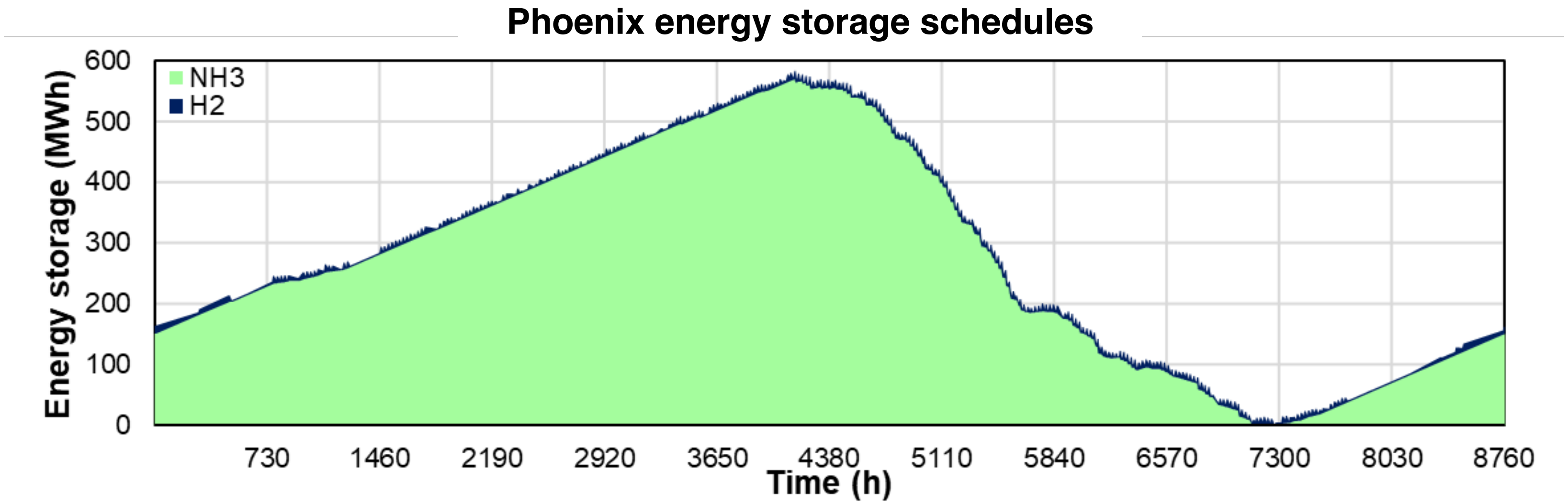


Combination of H_2 and NH_3 is optimal in all locations

Optimal Storage Schedules

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





H_2 fast, NH_3 slow (seasonal) → Efficiency vs. storage cost

Conclusions

- Green ammonia: transformative potential
- Drop-in replacement in agriculture with significant sustainability and price stability benefits
- Flexible utilization as a fuel
- Sector coupling can improve economic competitiveness
- A key piece of the clean energy storage puzzle

Future Outlook – Ammonia Production

- Haber-Bosch process still state-of-the-art
- Separation alternatives: absorption, membranes,…
- Catalysis alternatives
- Electrochemical synthesis
- Seawater electrolysis, offshore production
- Dynamic operation

Future Outlook - Utilization

- Ammonia combustion
  - NO_x, N_2O mitigation
  - Fuel cell development and commercialization

- Inherently safe storage and transportation
  - Enable broad adoption

- New opportunities
  - Urea production using captured CO_2
  - Dispatchable power generation
  - Maritime transportation – green corridors
  - Fuel for trains, barges, trucks

Next Generation Ammonia from Wind and Solar

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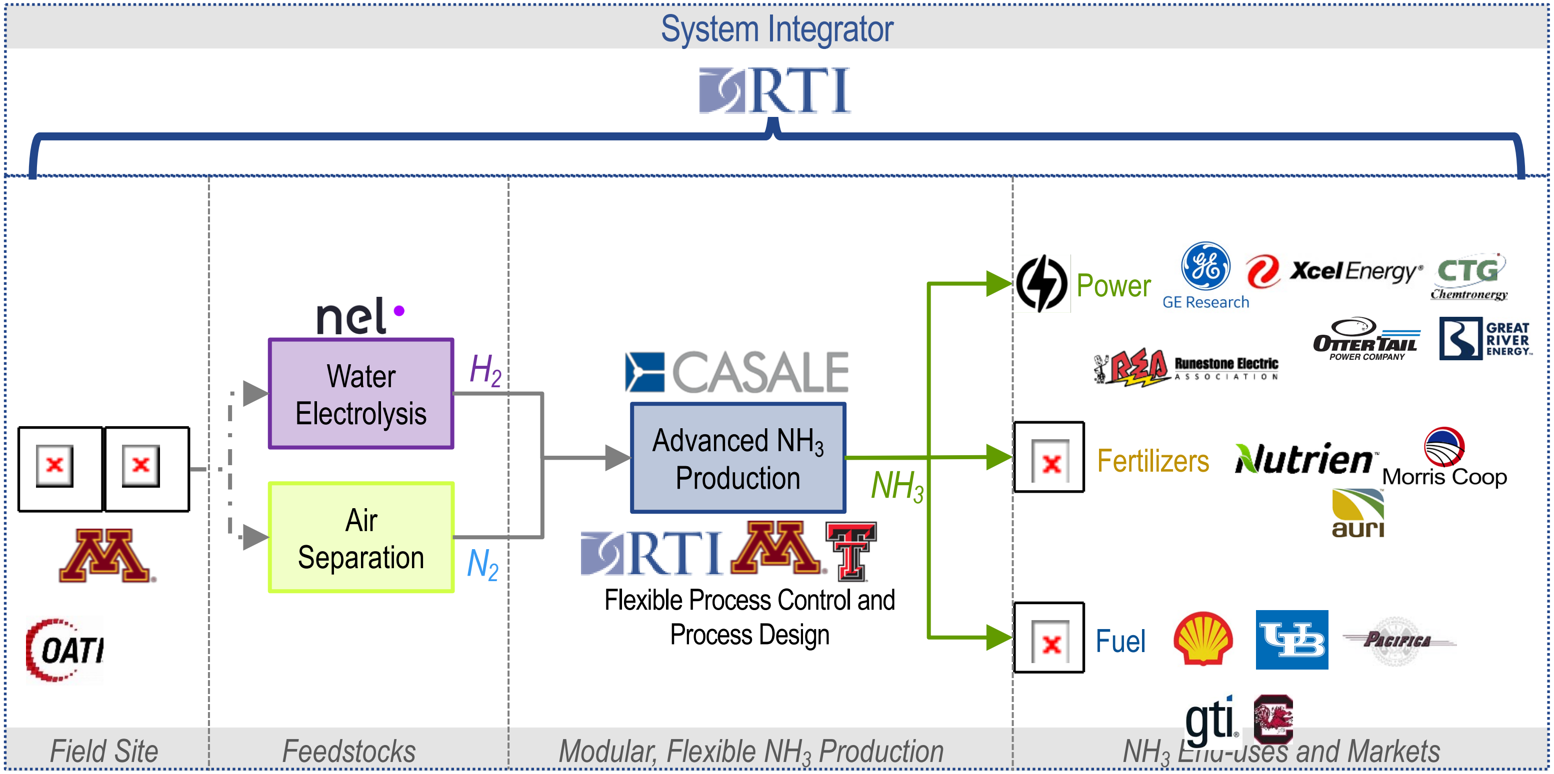

Next-gen NH_3 production and utilization technologies	**Demonstrate under real-world conditions**	**Connect with end-users and markets to accelerate commercialization**

Future Outlook - Broader Challenges

- Capital intensive (>100MM$) investments required
    - How can the farmers be part of the solution?
- Green hydrogen at scale
    - Can electrolysis supply keep up with demand?
    - Effect on cost of electrolyzers?
- Green ammonia certification and market design
- Public perception and acceptance

Acknowledgements

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