Combined Design and Scheduling Optimization of a Distributed Sustainable Energy Agriculture (DSEA) System

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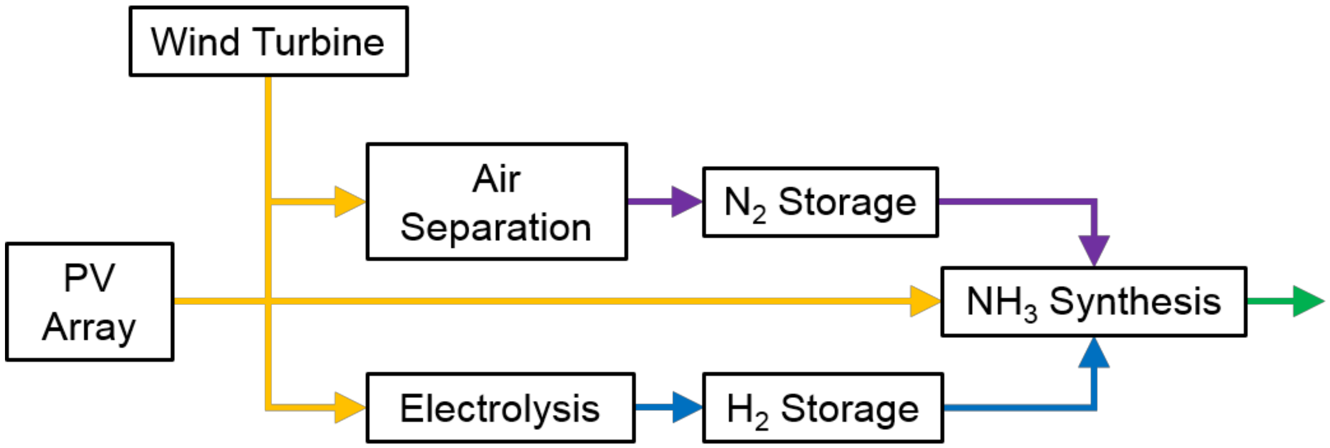
Motivation: Small-Scale Renewable Power to Ammonia

- Small-scale, distributed for transportation reduction, easier use of renewables
- Wind-powered Haber-Bosch in Morris, MN[1]
- Solar power: Raphael Schmuecker Memorial Farm in Iowa[2]
- Optimization of design and operation[3-5]



Loss of economies of scale: High capital cost

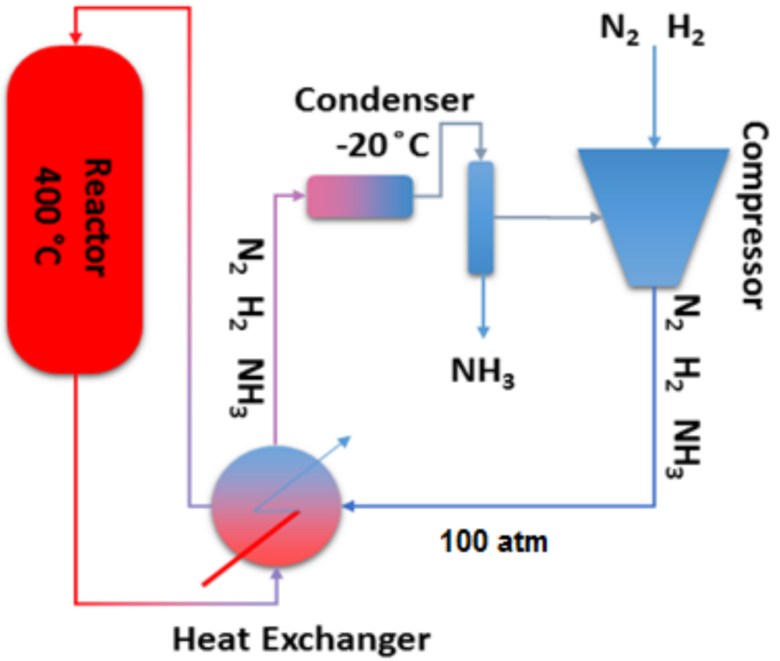
Energy storage needed: batteries too expensive

[1] Reese et. al, *Ind. Eng. Chem. Res.* 2016, 55, 3742-3750.
[2] Schmuecker, *11th Annual Ammonia Fuel Conference*, 2014.
[3] Beerbuhl et. al, *Eur. J. Oper. Res.* 2015, 241, 851-862.
[4] Sanchez and Martin, *J. Clean. Prod.* 2018, 178, 325-342.
[5] Allman et al, *AIChE J.*, 2018, Accepted, DOI: 10.1002/aic.16434.

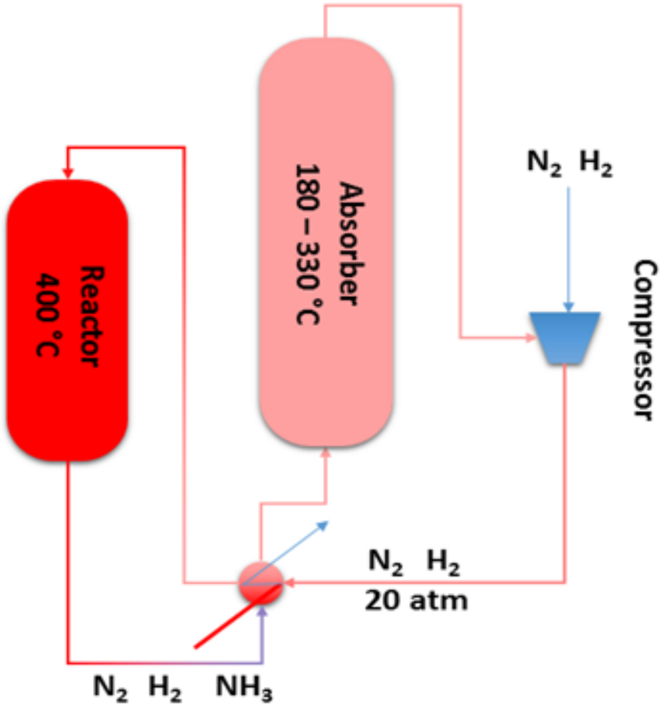
Lowering Capital Cost: Absorbent Enhanced Synthesis

- Absorption instead of condensation[1]
- Lower pressure and less heat exchange (temperature difference)
- Lower capital cost than conventional process, especially at small scale[2]

Haber Process



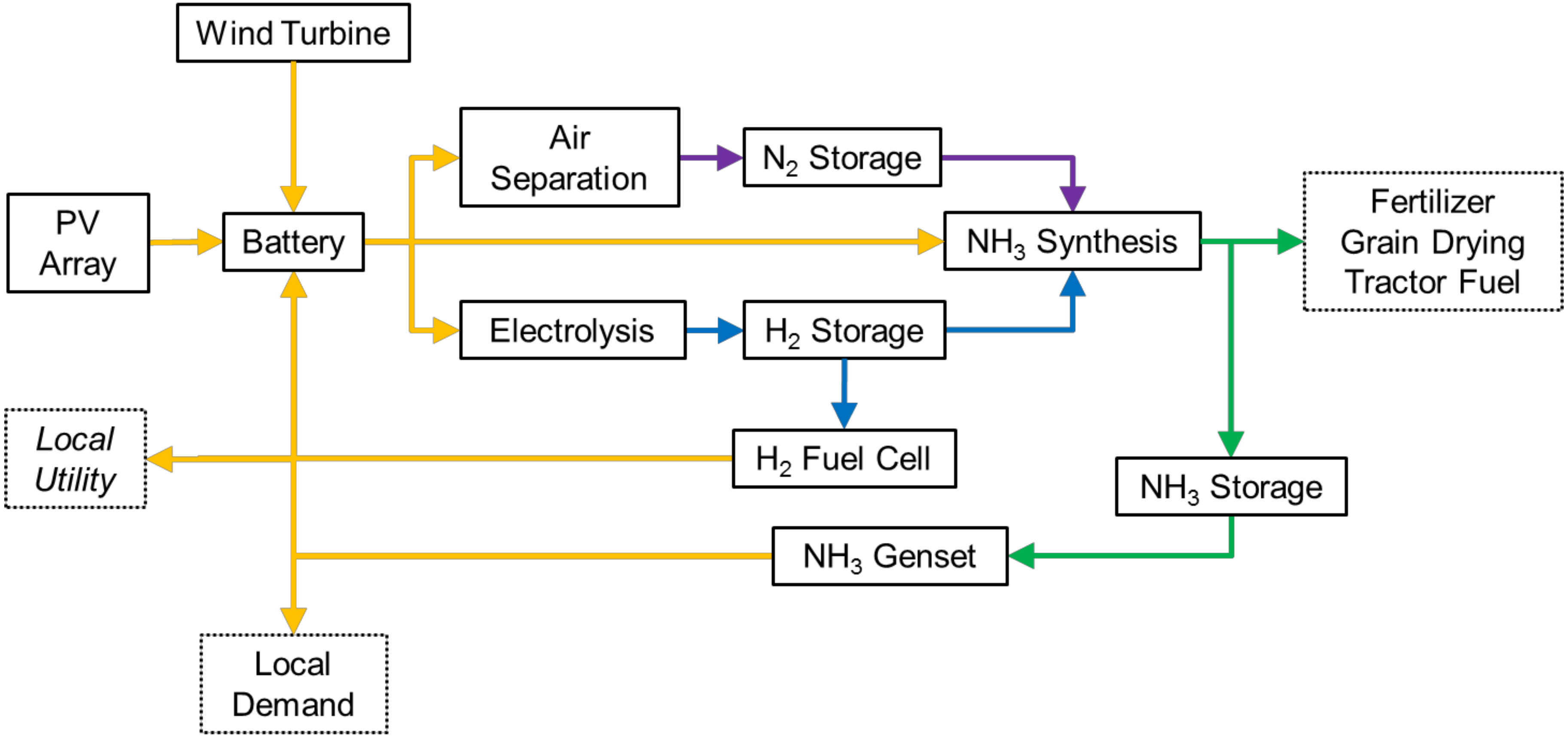
Absorbent Enhanced Process



[1] Malmali et al, *Ind. Eng. Chem. Res.,* 2016, 55, 33, 8922-8932.
[2] Palys et al, *Processes*, 2018, 6, 7, 91.

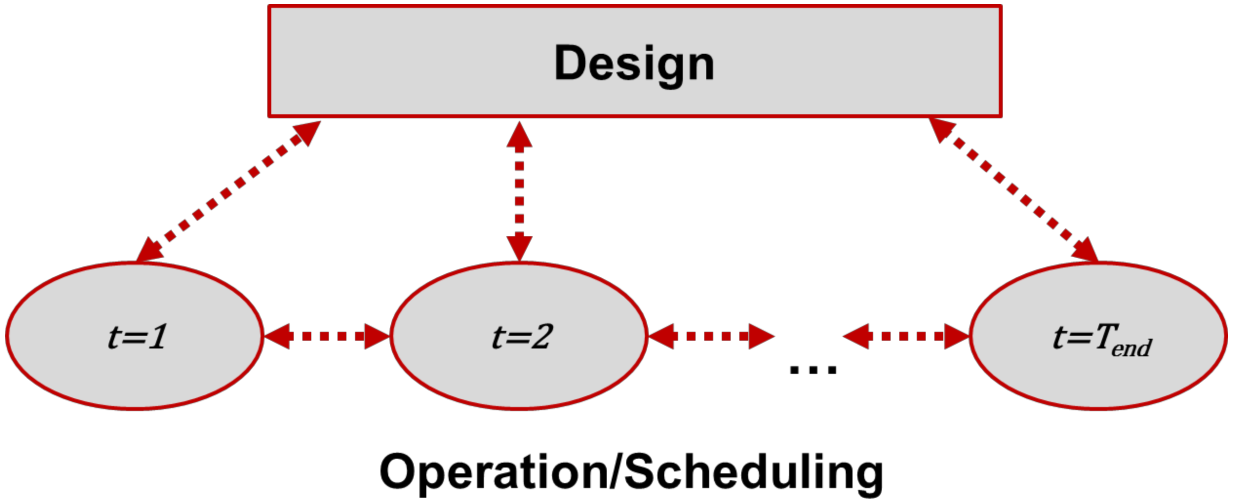
Distributed Sustainable Energy Agriculture (DSEA) System

1. Ammonia and hydrogen as local energy storage media
2. Ammonia for sustainable agriculture: fertilizer, *grain drying* and *tractor fuel*
3. Collocated with local electrical load
4. Predictable and consistent power export for revenue and grid sustainability



How should we design the DSEA system?

- Economics: Lowest possible cost
- Operation of system is time varying
  - Hourly (or less) and seasonal
- System design and time varying operating schedule are coupled
  - Difficult to design using intuition, rules of thumb



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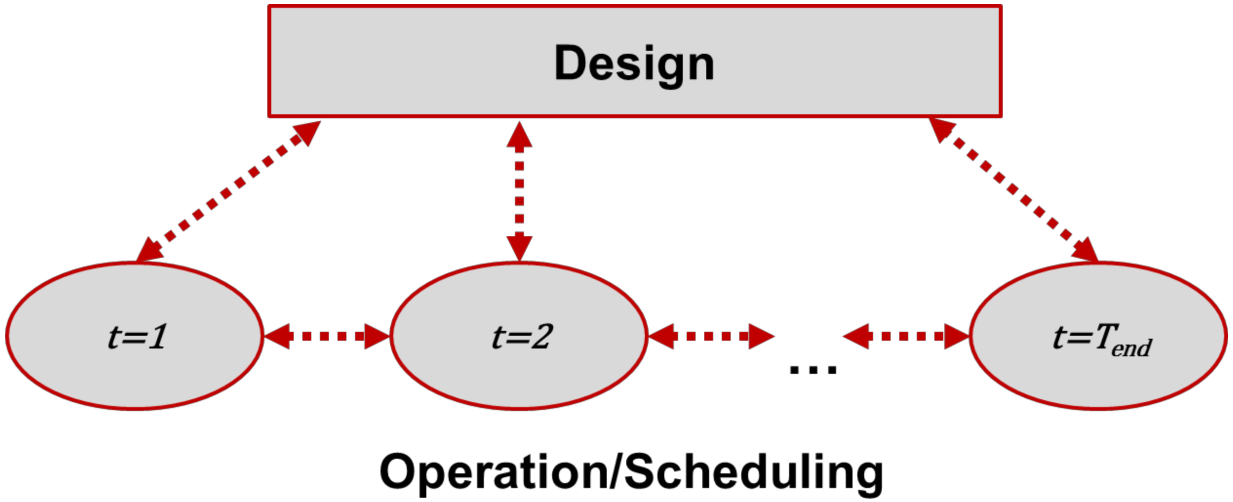


This Work: Combined Design-Scheduling Optimization

Optimal Combined Design and Scheduling of DSEA

Objective: Minimize sum of annualized capital and operating costs minus revenue from power sales

- Design decisions: Selection and size of process units (*made once*)
- Operating decisions: Unit production rates, flows of mass and energy (*made for each operating period*)

Optimal Combined Design and Scheduling of DSEA

Objective: Minimize sum of annualized capital and operating costs minus revenue from power sales

- Design decisions: Selection and size of process units (*made once*)
- Operating decisions: Unit production rates, flows of mass and energy (*made for each operating period*)

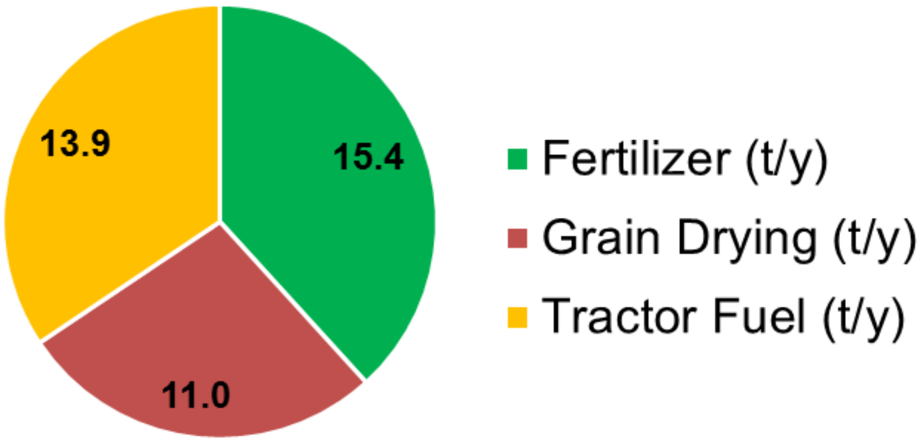
Constraints:

- Seasonal ammonia demand
- Power balance (hourly)
- Power sale regulation
- Inventory balances for storage units
- Unit operating constraints: *relates design and operation*

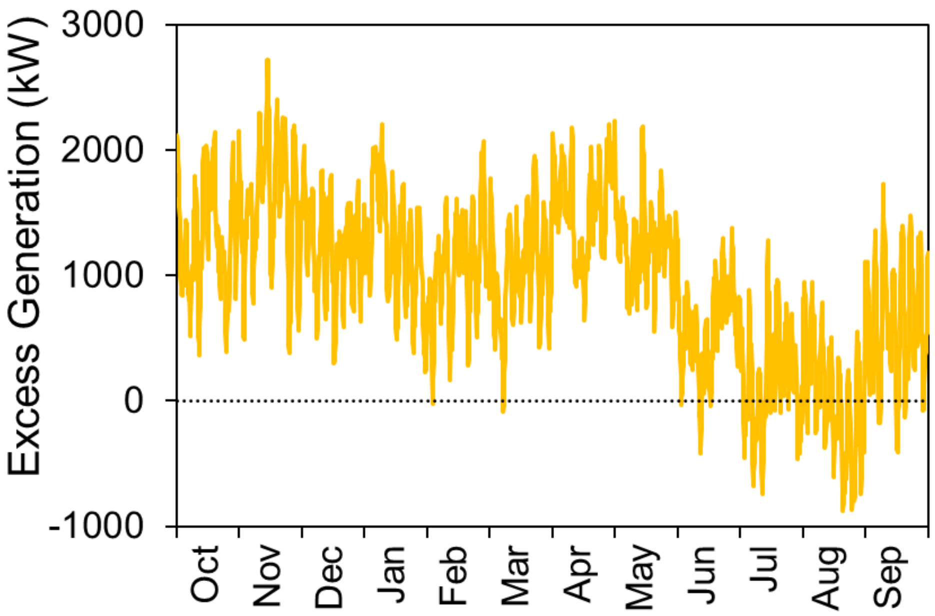
WCROC-UMM Morris Case Study

- Two 1.65 MW wind turbines in Morris
- Ammonia for WCROC farm, approximately 40 ton/year
  - 280 acres corn, 116 acres soy
- UMM Campus electrical load (annual average of 985 kWh)

WCROC Agricultural Ammonia Demands[1]



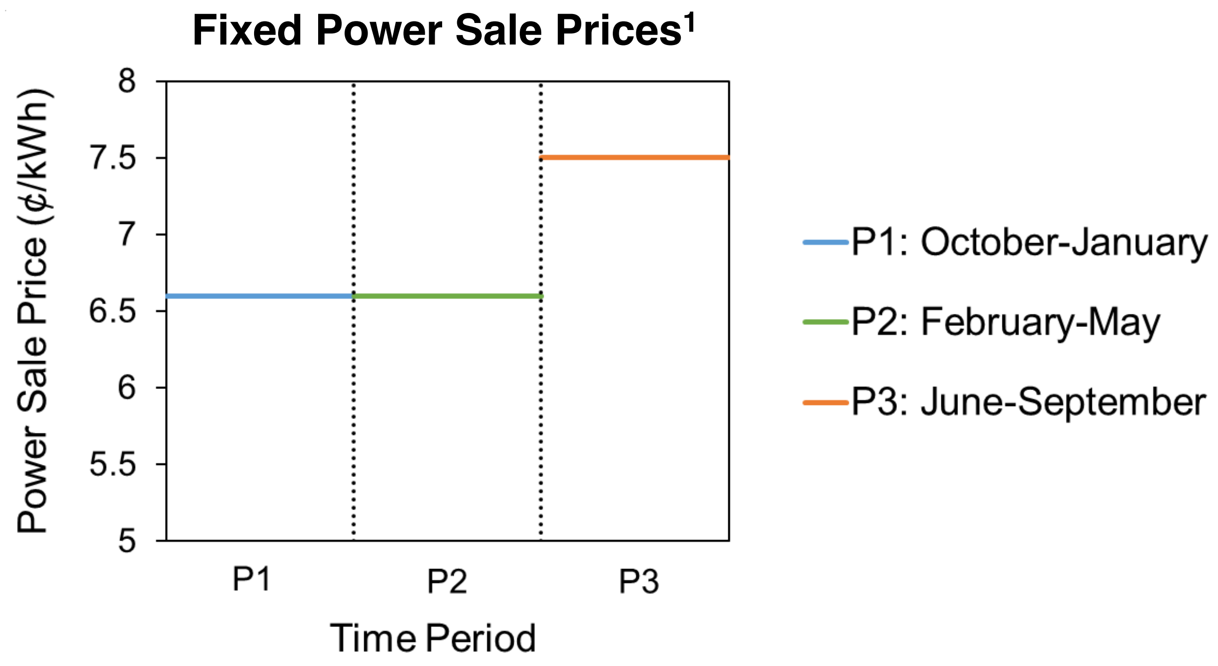
WCROC-UMM Excess Power Generation



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

WCROC-UMM Morris Case Study

- Two 1.65 MW wind turbines in Morris
- Ammonia for WCROC farm, approximately 40 ton/year
  - 280 acres corn, 116 acres soy
- UMM Campus electrical load (annual average of 985 kWh)
- Fixed power sale over three periods



[1] Xcel Energy, *Minnesota Commercial and Industrial Electric Prices*, 2018.

Results: DSEA Optimal Economics

- Net Present Cost: $97,000/year
  - 4.6 MM$ capital investment
  - $310,000/year profit from power sales

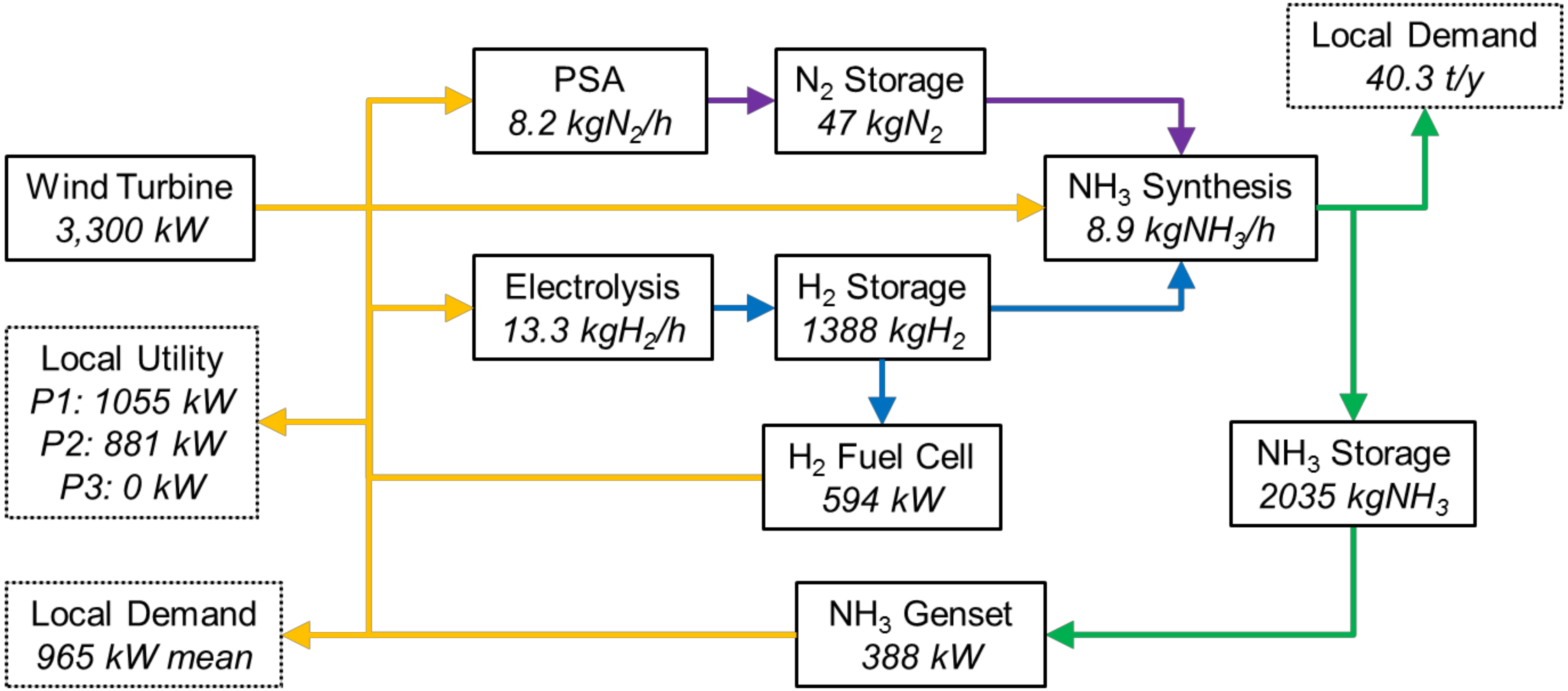
- Saves annually: ~$37,000/year
  - 15.4 tons of purchased ammonia fertilizer ($650/ton[1])
  - 276,000 ft^3 of natural gas ($3.20/thousand cu. ft[2])
  - 2200 gal of diesel ($7.60/gal[3])

Approximate annual cost: $60,000/year

[1] U.S. Department of Agriculture, *Anhydrous Ammonia Prices by Month from 2009 to 2018*, 2018.
[2] U.S. Energy Information Administration, *Minnesota Commercial Natural Gas Prices*, 2018.
[3] U.S. Energy Information Administration, *Midwest Diesel Retail Prices*, 2018.

Results: DSEA Optimal Design

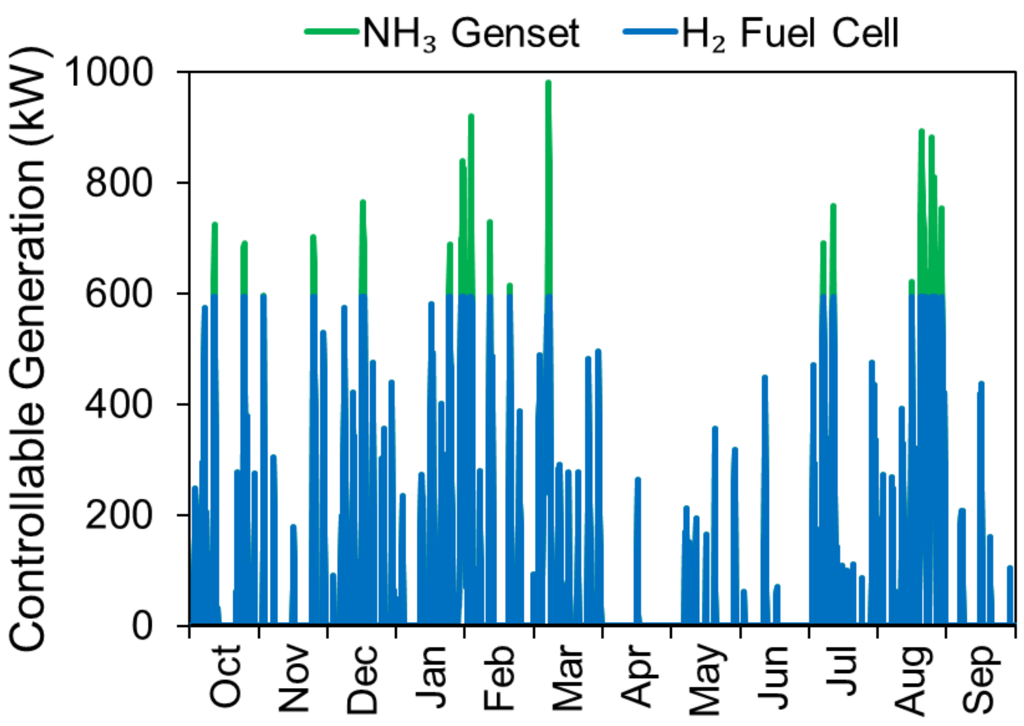
- No battery ← too expensive
- Annual average production levels (capacity fraction)
  - Synthesis: 83%
  - PSA: 74% ← nitrogen buffer storage
  - Electrolysis: 47% ← flexible production, significant for energy storage



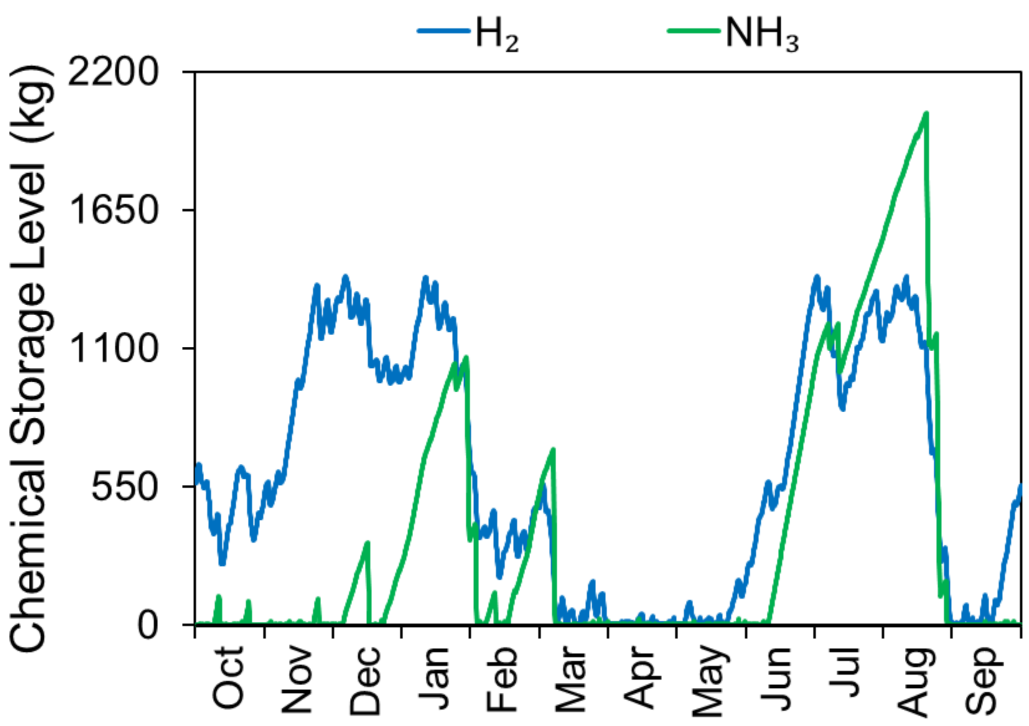
Results: DSEA Optimal Schedule

- Hydrogen: main method of energy storage
- Ammonia: storage evolves more slowly, used only during critical periods
- Tradeoff between overall energy efficiency (H_2) and storage cost (NH_3)

Controllable Generation Schedule



Chemical Storage Schedule



Conclusions

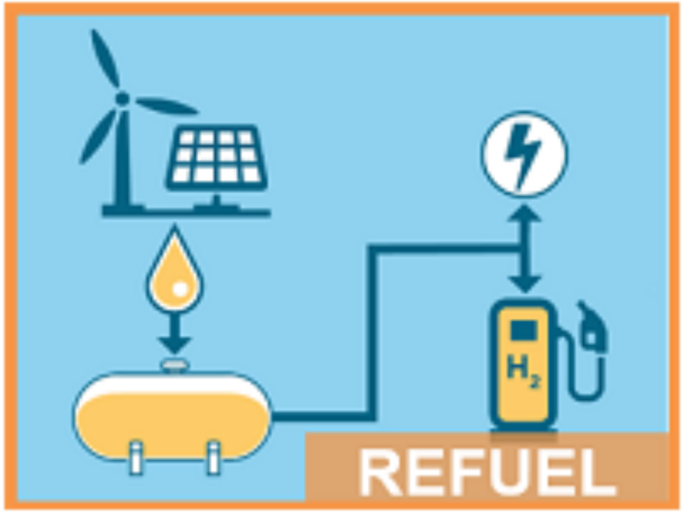
- A new vision for sustainable agriculture and energy supply, facilitated by ammonia

- Renewable power with hydrogen and ammonia as local energy storage for:
  - Ammonia as fertilizer, tractor fuel, grain drying
  - Local electrical power demands
  - Predictable and consistent power export to utility

- Simultaneous optimization of design and schedule
  - First attempt to take advantage of synergies: Annual cost of ~$60,000/year
  - Both hydrogen and ammonia used as energy storage

Acknowledgements

- Daoutidis Group (pictured)
- UMN Refuel Project Team
- **ARPA-E Refuel Program**
  - Grant USDOE / DE-AR0000804



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WCROC-UMM Morris Case Study Data

- Candidate units:
  - Electrolysis: 50 kWh/kgH_2
  - PSA: 1.6 kWh/kgN_2
  - Absorbent enhanced synthesis: 3.1 kWh/kgNH_3
  - Battery: $600/kWh
  - Chemical storage: $50/kWh H_2, $3.25/kWh NH_3
  - Hydrogen fuel cell: 60% LHV efficiency
  - Ammonia genset: 30% LHV efficiency

DSEA Optimization: Sensitivity Analysis