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

Matthew J. Palys, Anatoliy Kuznetsov, Prodromos Daoutidis
Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, MN

Joel Tallaksen, Michael Reese
West Central Research and Outreach Center, Morris, MN

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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\textsuperscript{1}
- Solar power: Raphael Schmuecker Memorial Farm in Iowa\textsuperscript{2}
- Optimization of design and operation\textsuperscript{3-5}

Loss of economies of scale: High capital cost
Energy storage needed: batteries too expensive

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\(^2\)

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
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-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

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/ton¹)
  - 276,000 ft³ of natural gas ($3.20/thousand cu. ft²)
  - 2200 gal of diesel ($7.60/gal³)

Approximate annual cost: $60,000/year

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 ($NH_3$)
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
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WCROC-UMM Morris Case Study Data

- Candidate units:
  - Electrolysis: 50 kWh/kgH₂
  - PSA: 1.6 kWh/kgN₂
  - Absorbent enhanced synthesis: 3.1 kWh/kgNH₃
  - Battery: $600/kWh
  - Chemical storage: $50/kWh H₂, $3.25/kWh NH₃
  - Hydrogen fuel cell: 60% LHV efficiency
  - Ammonia genset: 30% LHV efficiency
DSEA Optimization: Sensitivity Analysis

- Synthesis Capital Cost
- Synthesis Energy Efficiency
- Synthesis Flexibility
- Genset Capital Cost
- Genset Energy Efficiency
- Base Case