Reduction in Cycling of the Boilers by Using Large-Scale Energy Storage of Cryogenic Carbon Capture

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Outline

- Background
- Cryogenic Carbon Capture
- Results
- Conclusion
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Motivation: CO$_2$ Emission

- Coal is the world’s principal energy supply
  - Global climate change concerns from CO$_2$

- Increasing Restriction for CO$_2$ Emission
  - EPA’s regulation for existing power plants (2015)
    - 30% reduction in CO$_2$ from 2005 levels by 2030
  - EPA’s regulation for new power plants (2015)
    - 1100 lbs/MWh CO$_2$ for gas-fired power plants
    - 1400 lbs/MWh CO$_2$ for coal-fired power plants

Trends in global CO$_2$ emissions, PBL Netherlands Environmental Assessment Agency, 2014
Motivation: Cycling Damage

Superheater Tube Damage

Header Cracking
Motivation: Cost of Spinning Reserves

Power Supply Curve
NREC Region, 2010

Low Utilization = High Cost / MWh
Hybrid System Enhances Renewable Adoption
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CO₂ Removal

- Oxy-combustion (1.69 MJₑ/kg CO₂)
- Chemical and Physical Absorption (1.72 MJₑ/kg CO₂)
- Membranes (1.3 MJₑ/kg CO₂)
- Cryogenic Carbon Capture (0.7 MJₑ/kg CO₂)
Advantages of the CCC Process

- Rapid-load-change capability
- Flexible operation
- Scalable energy storage
- Energy recovery with heat integration
Cryogenic Carbon Capture (CCC)

- Refrigerant Compression, Liquefaction, and Expansion
  - Contact Liquid Loop
  - Desublimating Tower
  - Solid Separation
  - Solid Compression
  - External Cooling Loop Refrigerant
  - Cool Liquid CO2

- CO2 Liquid
- Flue Gas
- N2-rich Light Gas
- Secondary Refrigerant
- Melting HX
- Ambient HX

Jensen, PhD Dissertation, Brigham Young University, 2015
Hybrid System of Power Generation and CCC

- Two refrigeration cycles
- Refrigerant is also the fuel
- Power produced with gas turbine
Improved Profitability through Integration

- Dynamic integration of CCC with power generation units
- Meet residential and CCC electricity demands
- Maximize operational profit of the hybrid system
- Minimize cycling of the coal power plant
Optimization Approach

- **Objective function**: $\ell_1$-norm
  \[
  x, y_m, u \min \Phi = w_{hi}^T e_{hi} + w_{ho}^T e_{lo} + y_m^T c_y + u^T c_u + \Delta u^T c_\Delta u
  \]

- **Dead-band for the controlled variable**
- **Prioritize multi-objective functions**
- **Active Set or Interior Point Solvers**
  - APOPT or IPOPT
- **APMonitor Modeling Language**

- **Constraints**
  \[
  0 = f(x, x, u, d) \\
  0 = g(y_x, x, u, d) \\
  a \geq h(x, u, d) \geq b \\
  \tau_c \frac{\delta y_{t,hi}}{\delta t} + y_{t,hi} = s_{phi} \\
  \tau_c \frac{\delta y_{t,lo}}{\delta t} + y_{t,lo} = s_{phi} \\
  e_{hi} \geq (y_m - y_{t,hi}) \\
  e_{lo} \geq (y_{t,lo} - y_m)
  \]
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Significant variations in coal power plant in load-following case

Variations in baseline case to avoid overproduction of power
Power Production vs. Electricity Demand

Baseline Boiler

- Meet the total electricity demand
- Refrigerant storage used in gas turbine
- 100% utilization of the wind power

Load-following Boiler
Trend of Natural Gas and LNG Inventory

Natural Gas (Baseline Boiler)

- Natural gas import during off-peak hours

LNG Inventory (Baseline Boiler)

- Natural gas export during peak hours

- LNG stored (kg)
- Power Price ($/MWh)
Impact of Energy Storage

With Energy Storage
1. Combined Cycle Power Production
2. Baseline Boiler

Without Energy Storage
1. Simple Cycle Power Production
2. Baseline Boiler

Compressor shifted to off-peak hours
Comparison of Power Production

Grounded Power = Total Power − Total Demand

With Energy Storage
1. Combined Cycle Power Production
2. Baseline Boiler

Without Energy Storage
1. Simple Cycle Power Production
2. Baseline Boiler

Power imbalance without energy storage
Cycling Cost

- Increased thermal, pressure, and mechanical related stress and fatigue
- Cycling costs from NREL report
- Cycling scenarios: Cold start, Hot start, Warm start, and Load-following
- Large scale subcritical coal power generation ($2.45/MW Capacity/Cycle)
- Natural gas combined cycle ($0.64/MW Capacity/Cycle)
Cycling Cost (Continued)

- Rainflow cycle counting algorithm
- Capacity of coal-fired generation unit: 1800 MW
- Capacity of coal-fired generation unit: 1000 MW

<table>
<thead>
<tr>
<th></th>
<th>With Wind</th>
<th>Without Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Load-following boiler</td>
<td>Baseline Boiler</td>
</tr>
<tr>
<td># cycles in Boiler (cost)</td>
<td>20 ($88200)</td>
<td>1 ($4410)</td>
</tr>
<tr>
<td># cycles in gas turbine (cost)</td>
<td>17 ($10880)</td>
<td>21 ($13440)</td>
</tr>
<tr>
<td>Total cycling costs</td>
<td>$99080</td>
<td>$17850</td>
</tr>
</tbody>
</table>

- Key Result: **80-85% reduction** in cycling damage with energy storage
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Conclusion

- CCC process removes 99% of CO$_2$ with lowest cost per kg CO$_2$
- Large-scale energy storage improves renewable adoption
- CCC + energy storage reduces cycling costs by 80-85%
- Future work: Power grid stability
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