# 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
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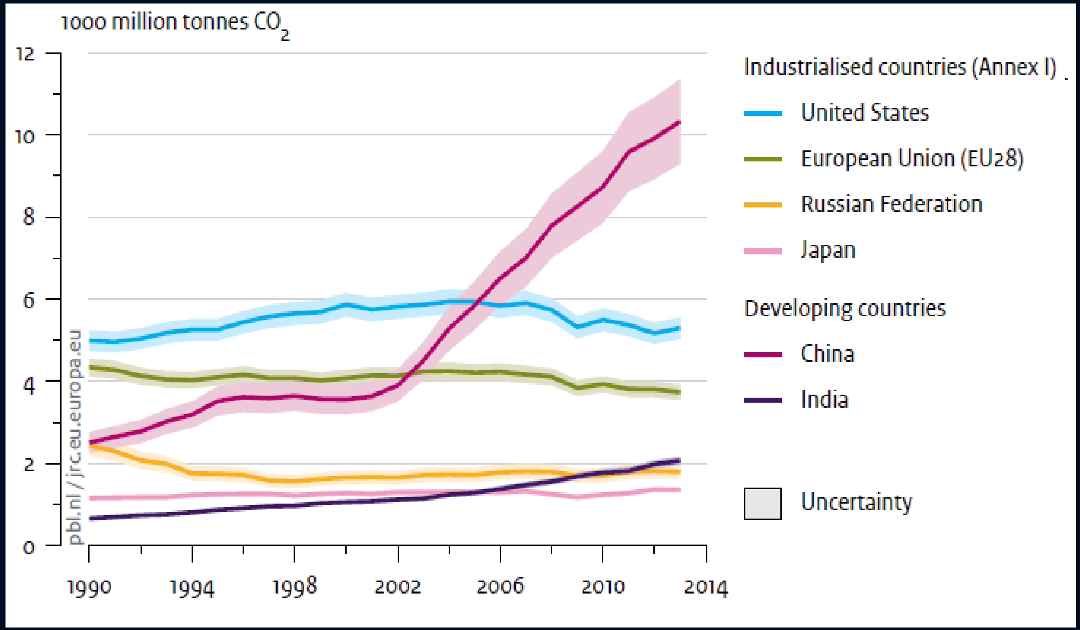
# Motivation: $CO_2$ Emission

- 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

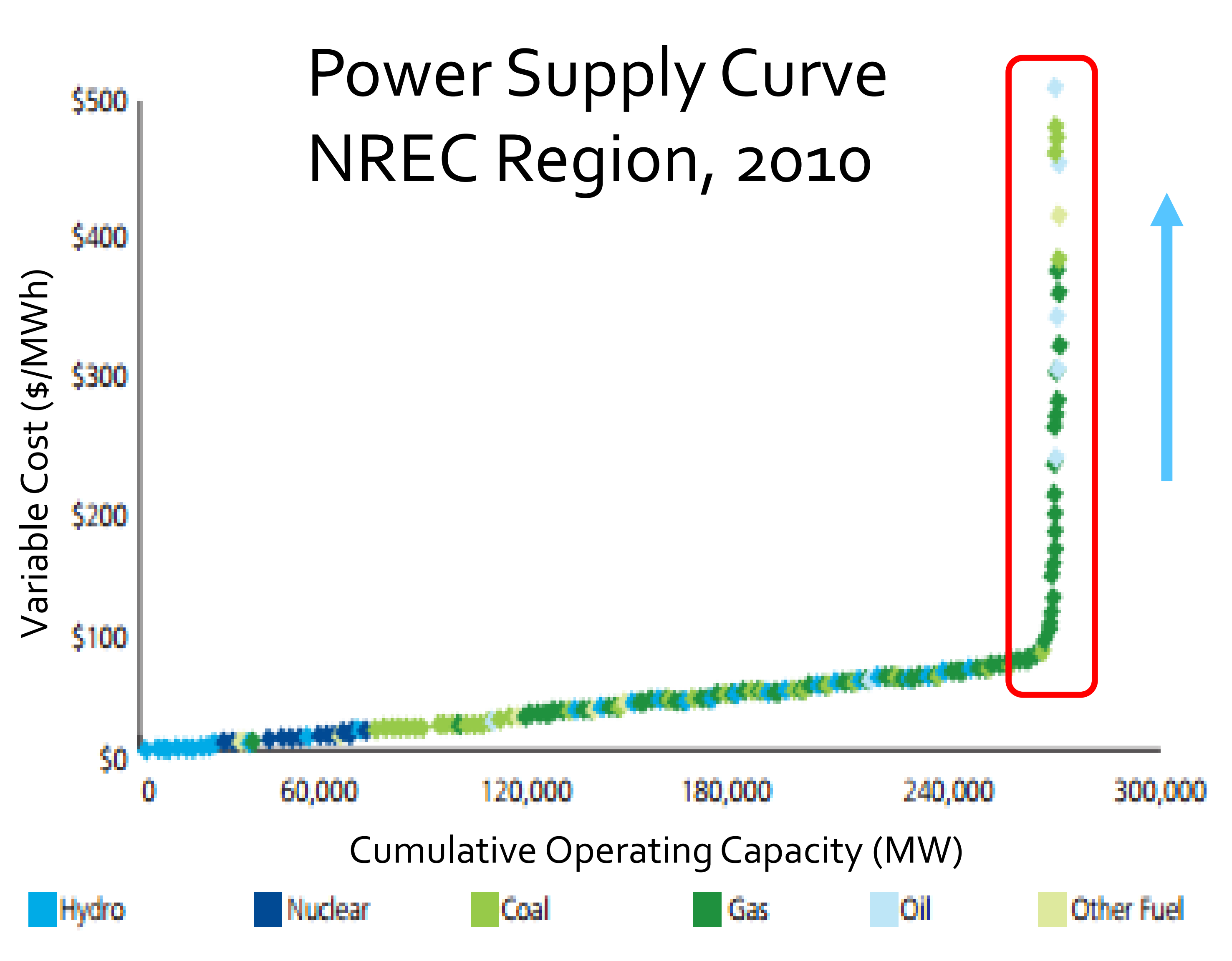
# Motivation: Cycling Damage





The Cost of Cycling Coal Fired Power Plants, Coal Power Magazine, 2006

# Motivation: Cost of Spinning Reserves

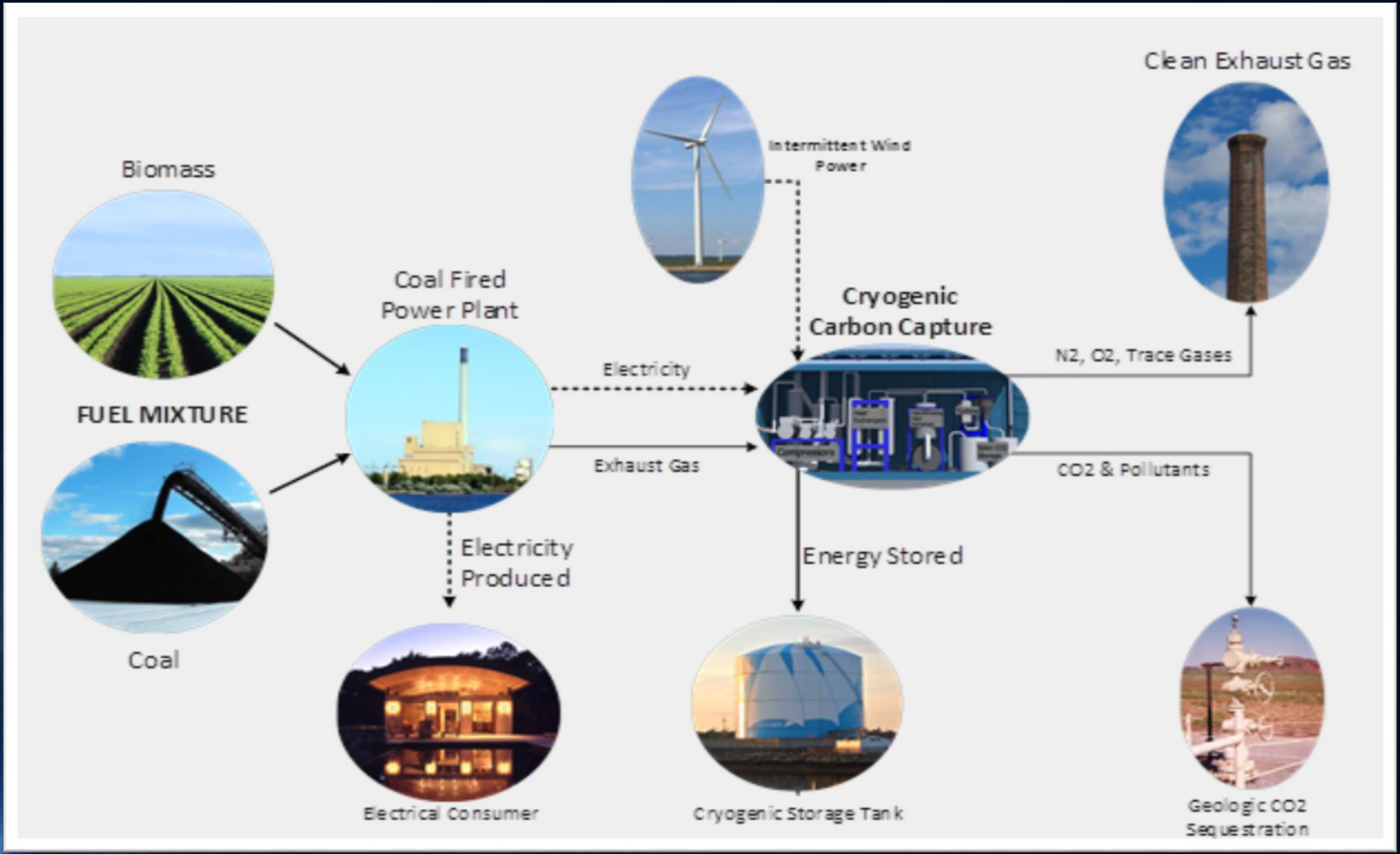



Low Utilization =
High Cost / MWh



Deloitte Center for Energy Solutions, 2011

# Hybrid System Enhances Renewable Adoption



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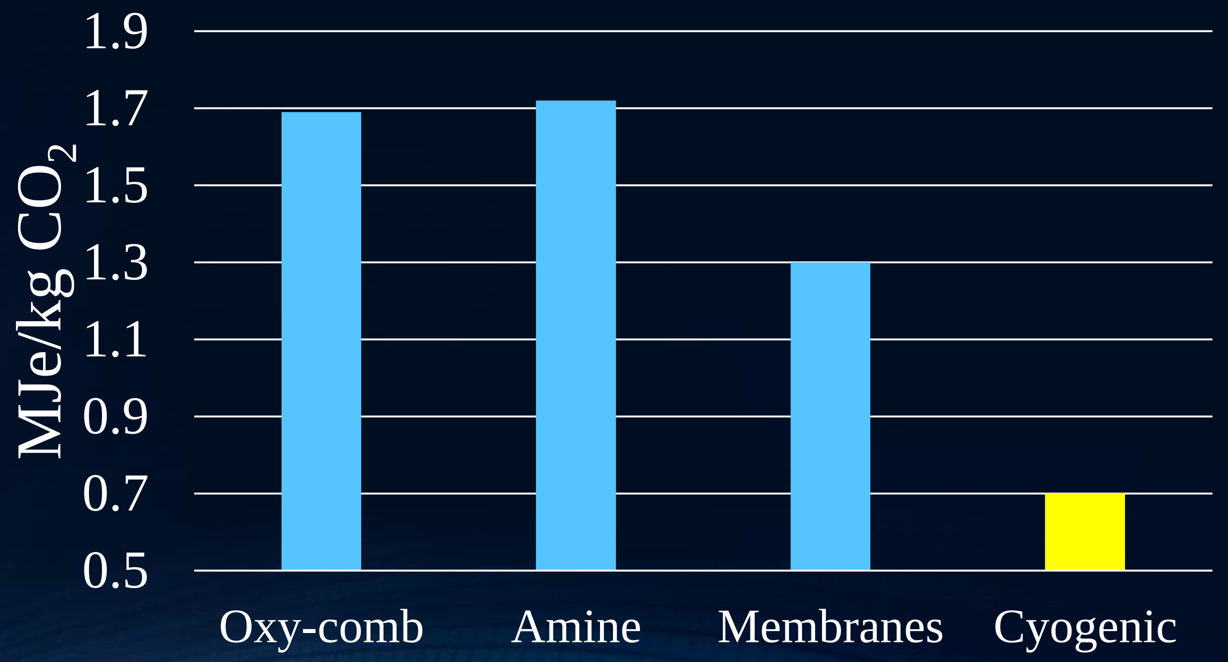
# $CO_2$ Removal

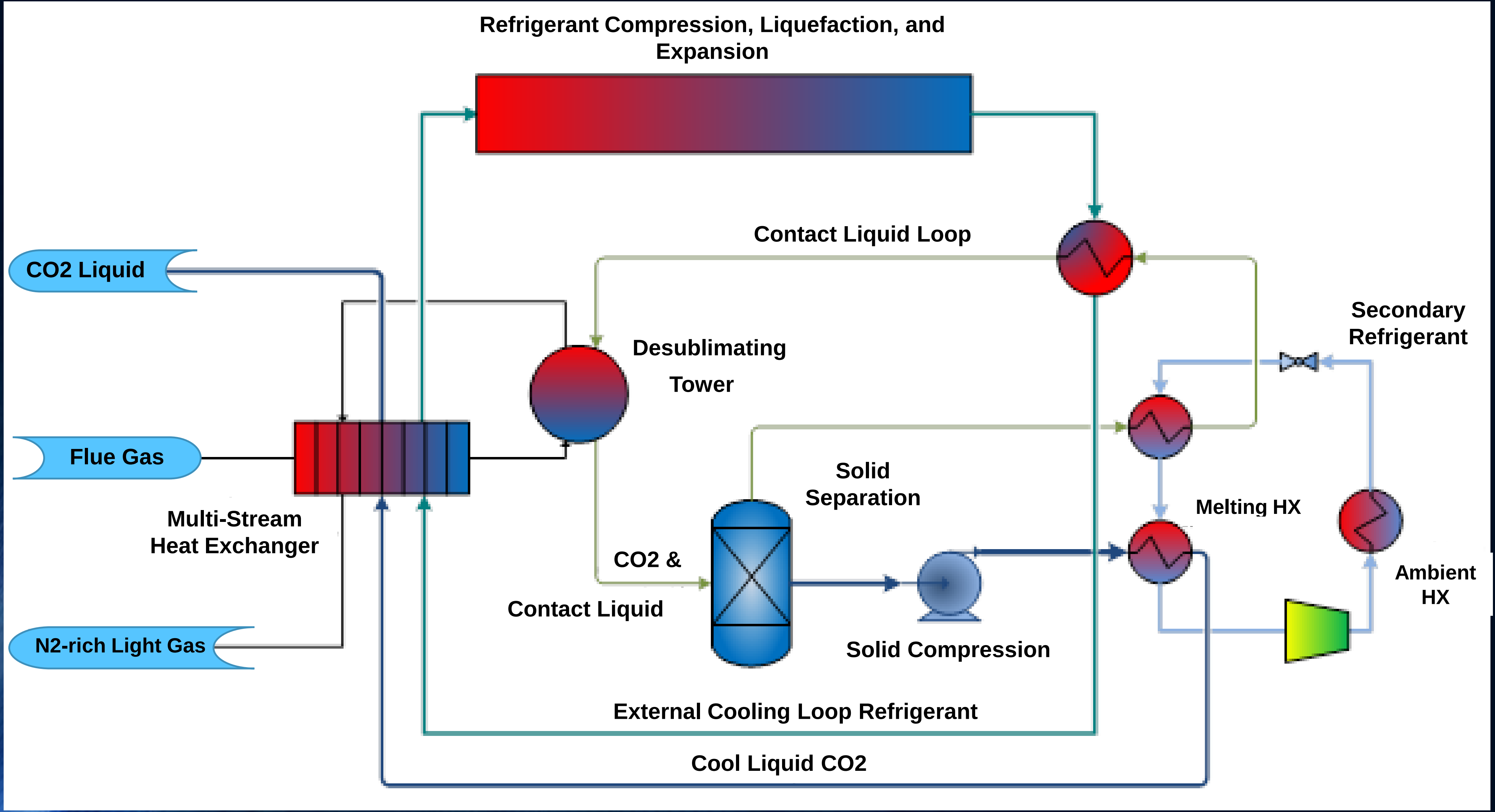
- Oxy-combustion (1.69 $MJ_e$/kg CO2)
- Chemical and Physical Absorption (1.72 $MJ_e$/kg $CO_2$)
- Membranes (1.3 $MJ_e$/kg $CO_2$)
- Cryogenic Carbon Capture (0.7 $MJ_e$/kg $CO_2$)



# Advantages of the CCC Process

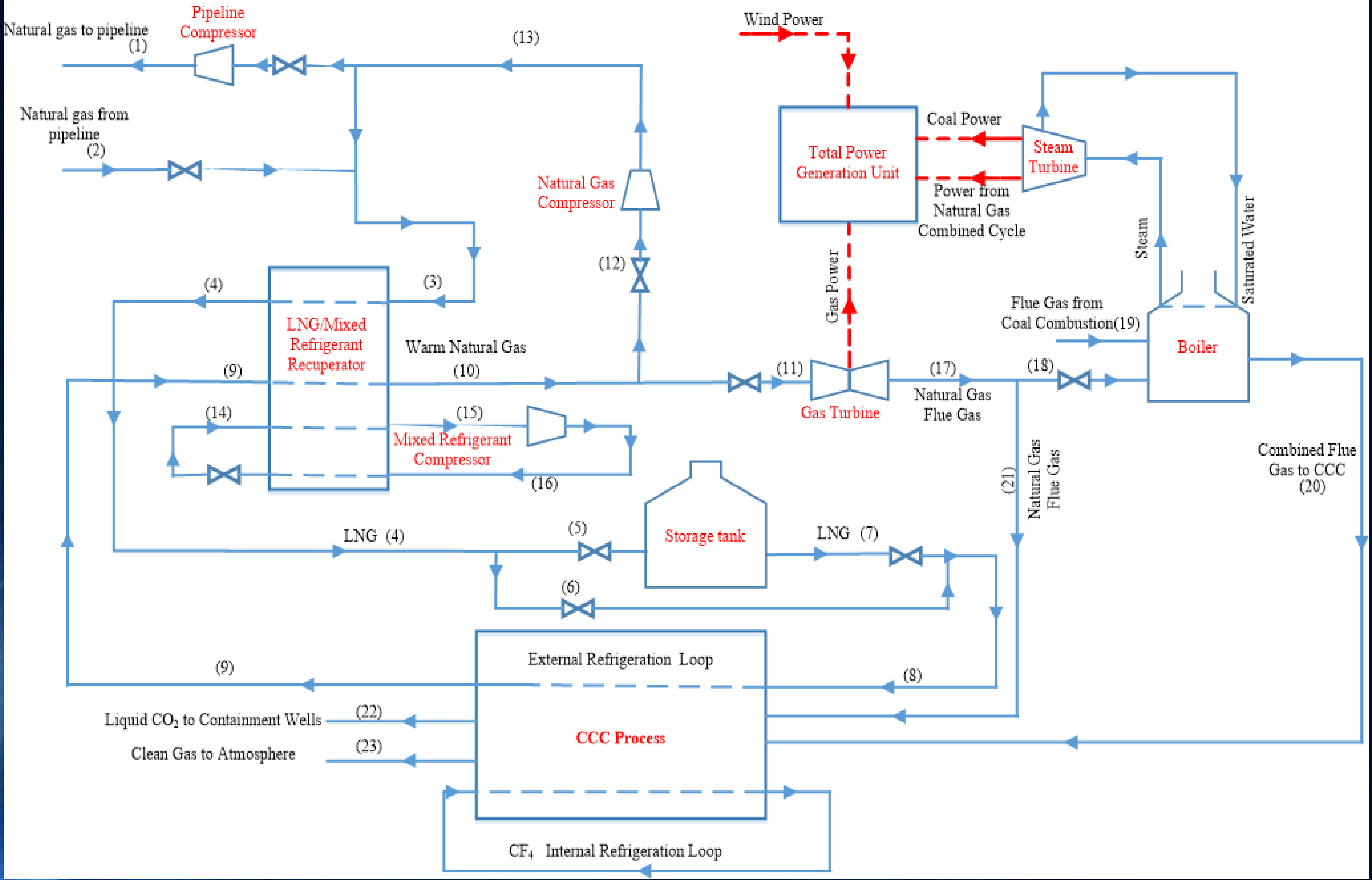
- Rapid-load-change capability
- Flexible operation
- Scalable energy storage
- Energy recovery with heat integration

# Cryogenic Carbon Capture (CCC)




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

$$\min_{x,y_m,u} \Phi = w_{hi}^T e_{hi} + w_{ho}^T e_{lo} + y_m^T c_y + u^T c_u + \Delta u^T c_{\Delta u}$$

$$s.t. \quad 0 = f(\dot{x}, x, u, d)$$

$$0 = g(y_x, x, u, d)$$

$$a \geq h(x, u, d) \geq b$$

$$\tau_c \frac{\delta y_{t,hi}}{\delta t} + y_{t,hi} = sp_{hi}$$

$$\tau_c \frac{\delta y_{t,lo}}{\delta t} + y_{t,lo} = sp_{lo}$$

$$e_{hi} \geq \left(y_m - y_{t,hi}\right)$$

$$e_{lo} \geq \left(y_{t,lo} - y_m\right)$$

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

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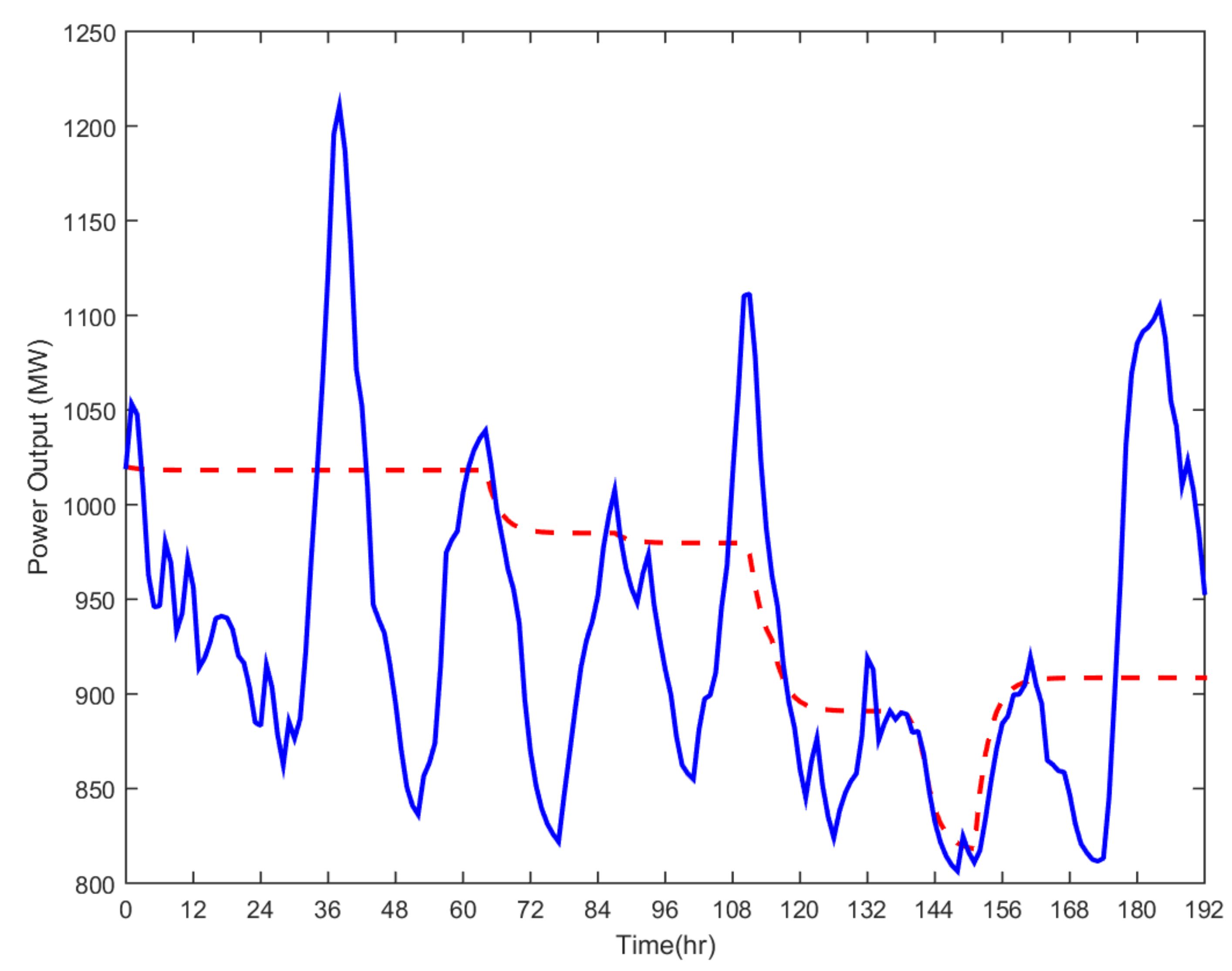
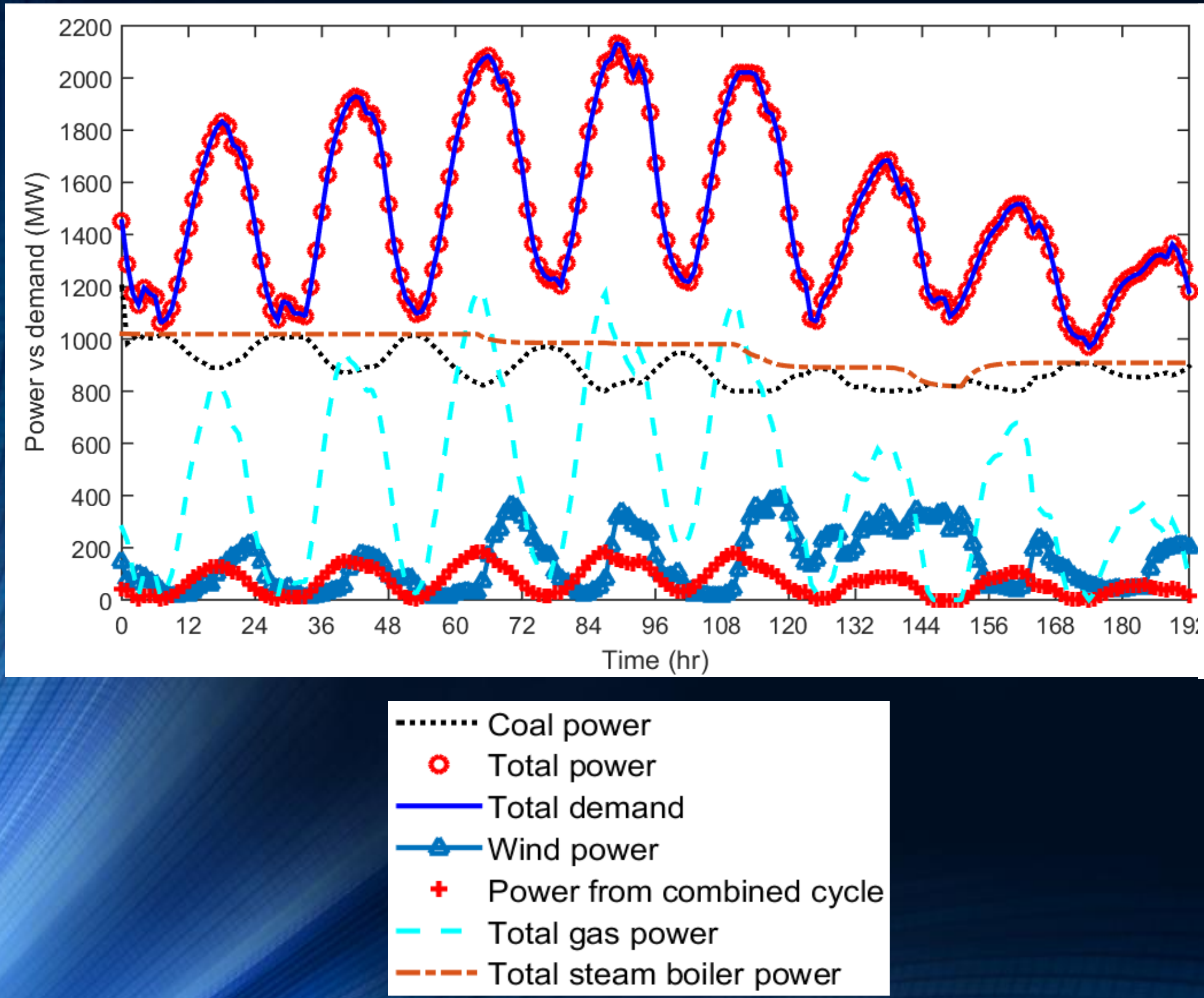
# Power Output from Coal Plant



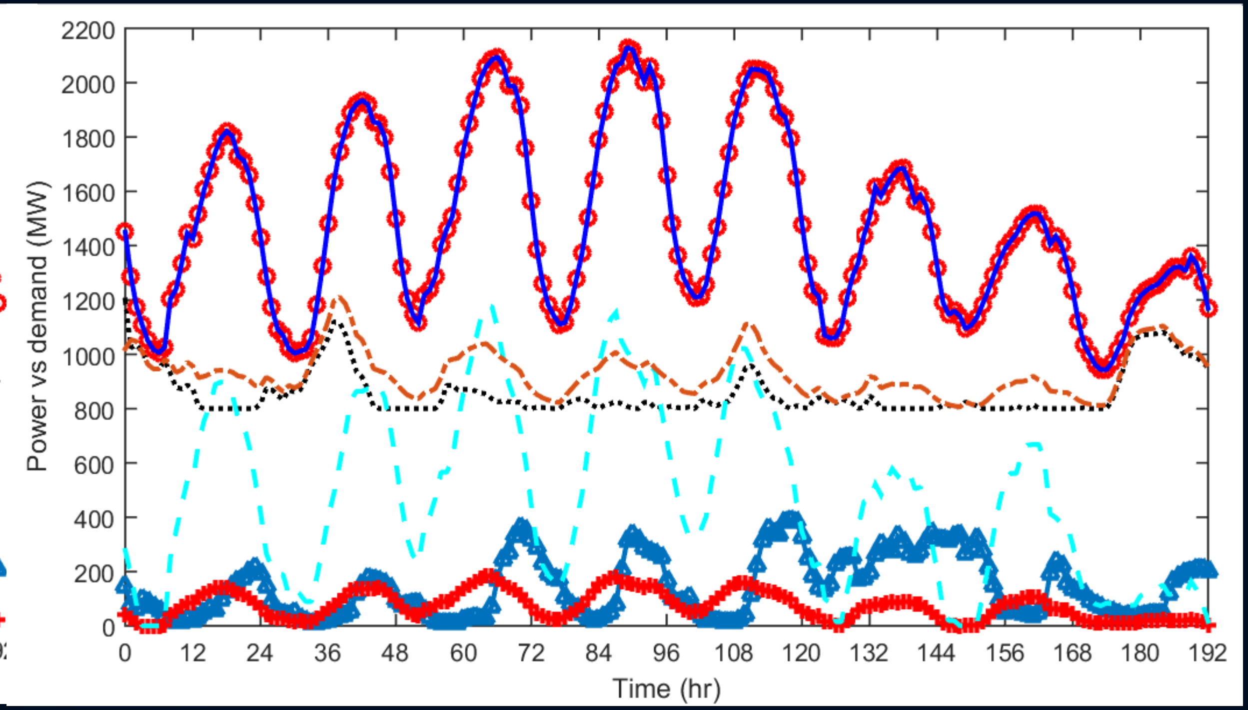

- Significant variations in coal power plant in load-following case
- Variations in baseline case to avoid overproduction of power

# Power Production vs. Electricity Demand

Baseline Boiler



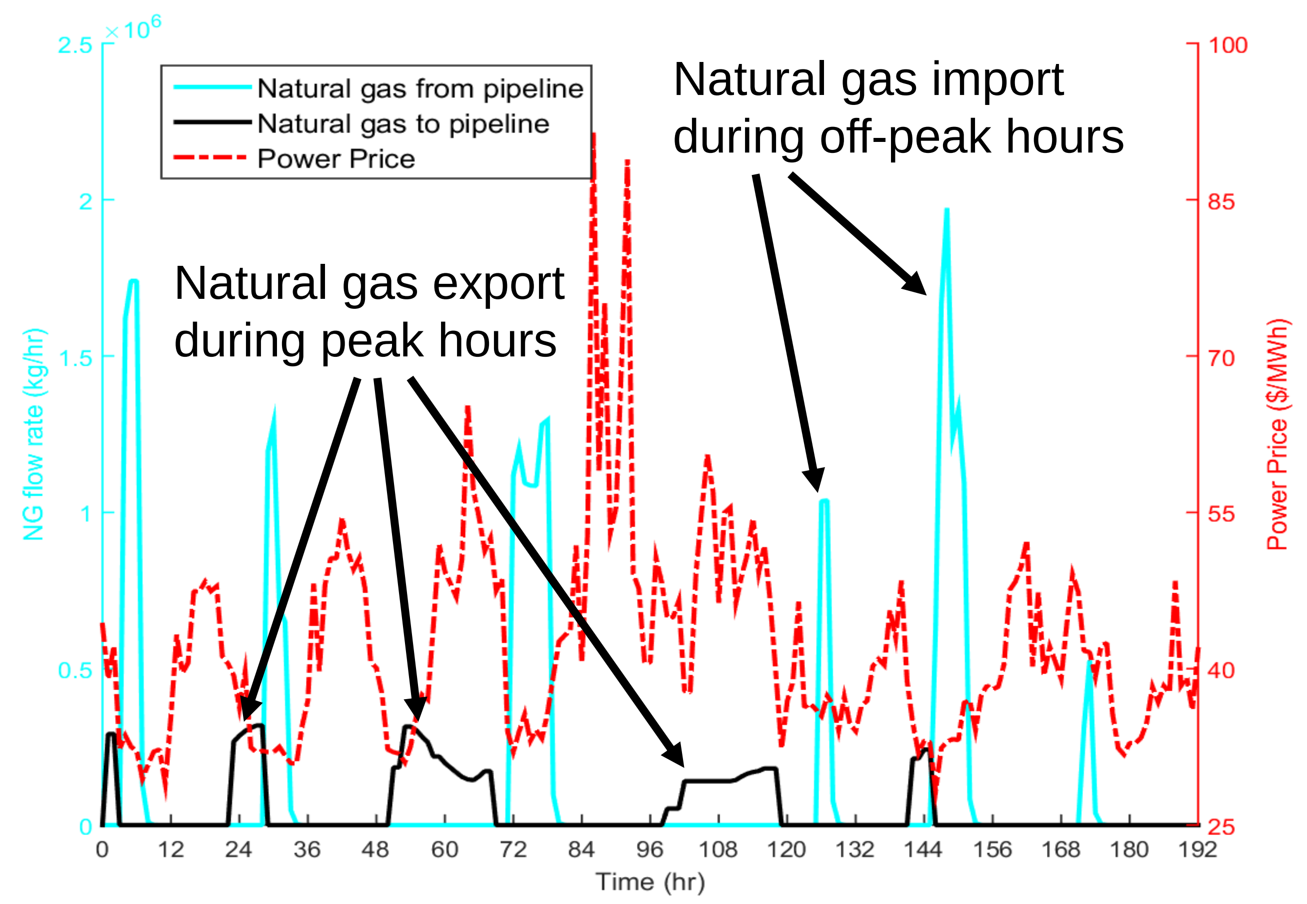

Load-following Boiler



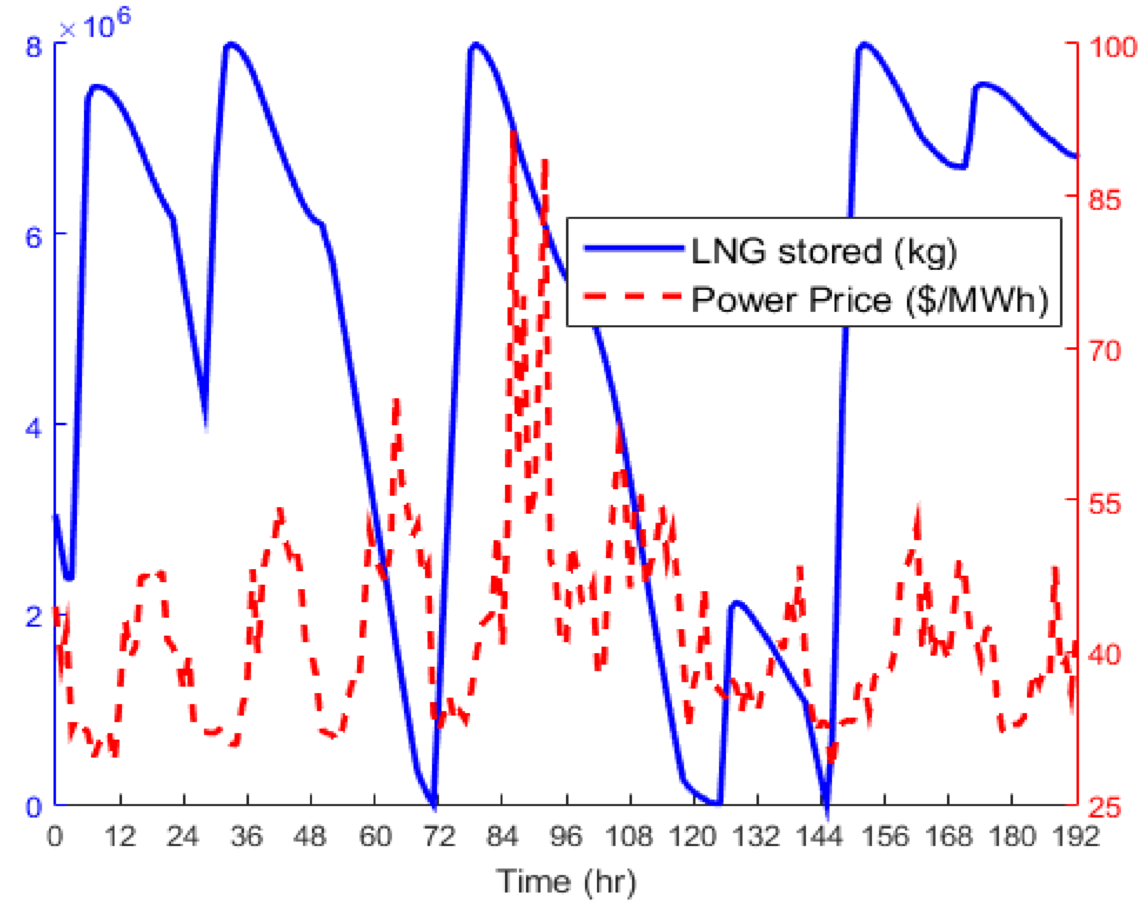

- Meet the total electricity demand
- Refrigerant storage used in gas turbine
- 100% utilization of the wind power

# Trend of Natural Gas and LNG Inventory

Natural Gas (Baseline Boiler)




LNG Inventory (Baseline Boiler)



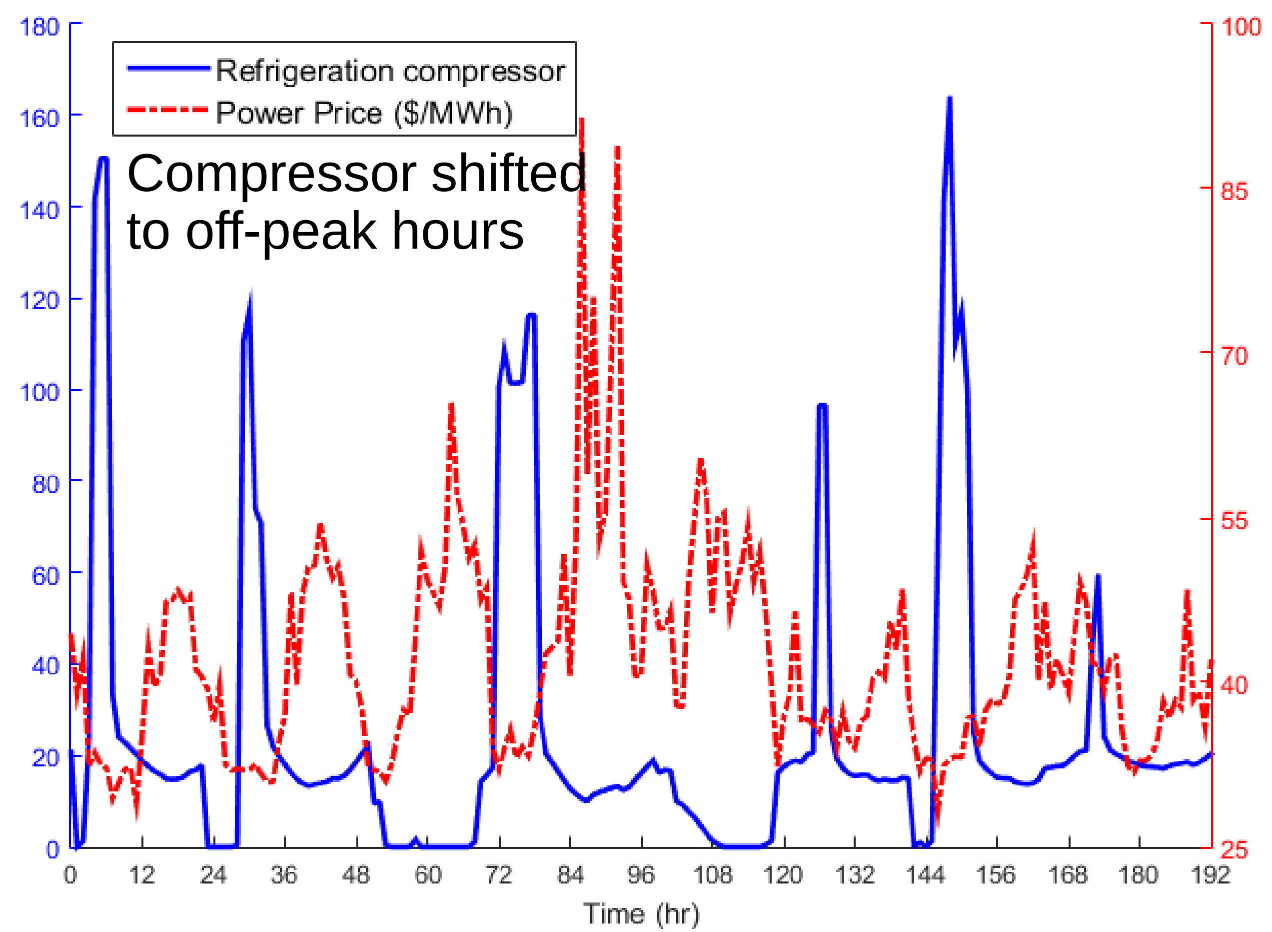
# Impact of Energy Storage

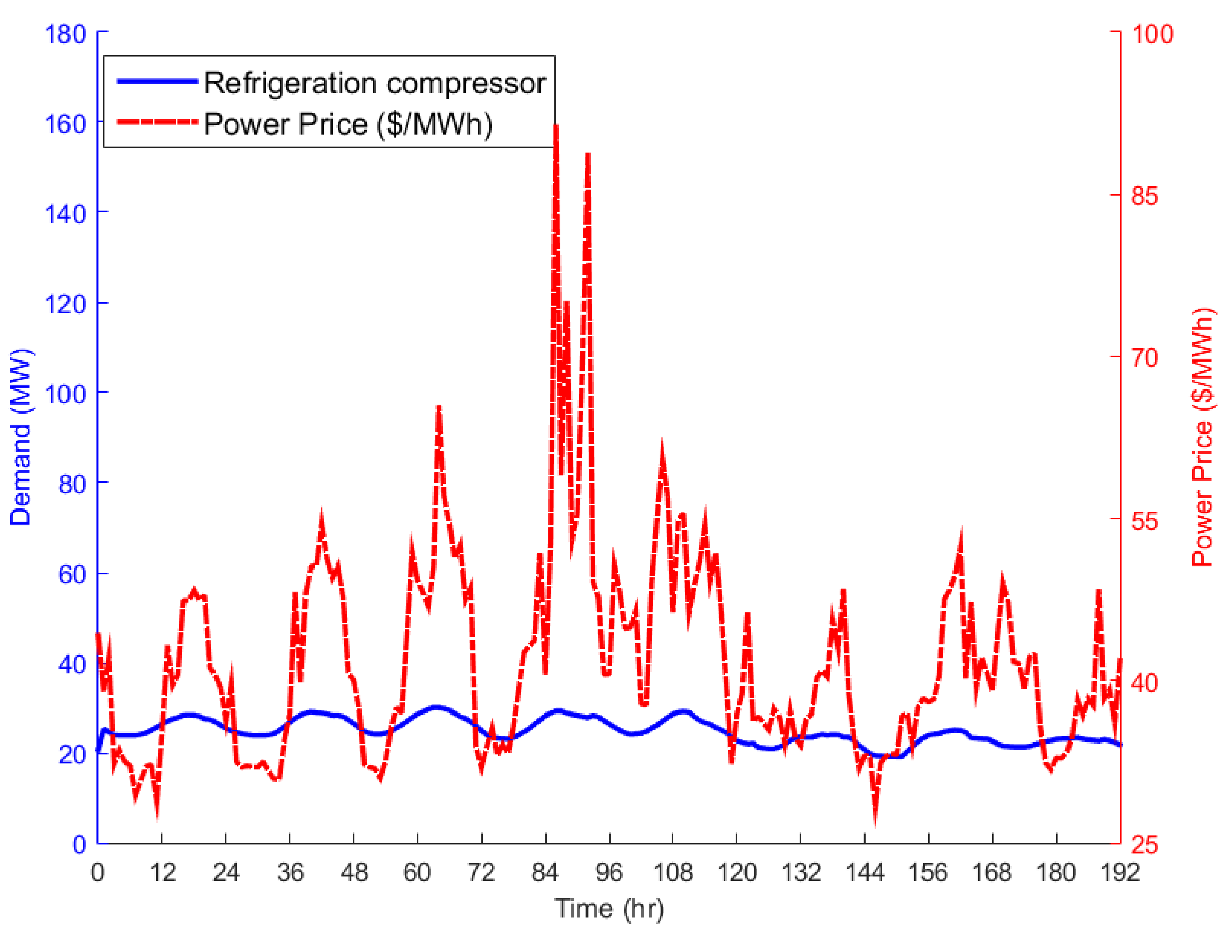
**With Energy Storage**

1. Combined Cycle Power Production
2. Baseline Boiler

**Without Energy Storage**

1. Simple Cycle Power Production
2. Baseline Boiler



# Comparison of Power Production

$$\textit{Grounded Power} = \textit{Total Power} - \textit{Total Demand}$$

**With Energy Storage**

1. Combined Cycle Power Production
2. Baseline Boiler

**Without Energy Storage**

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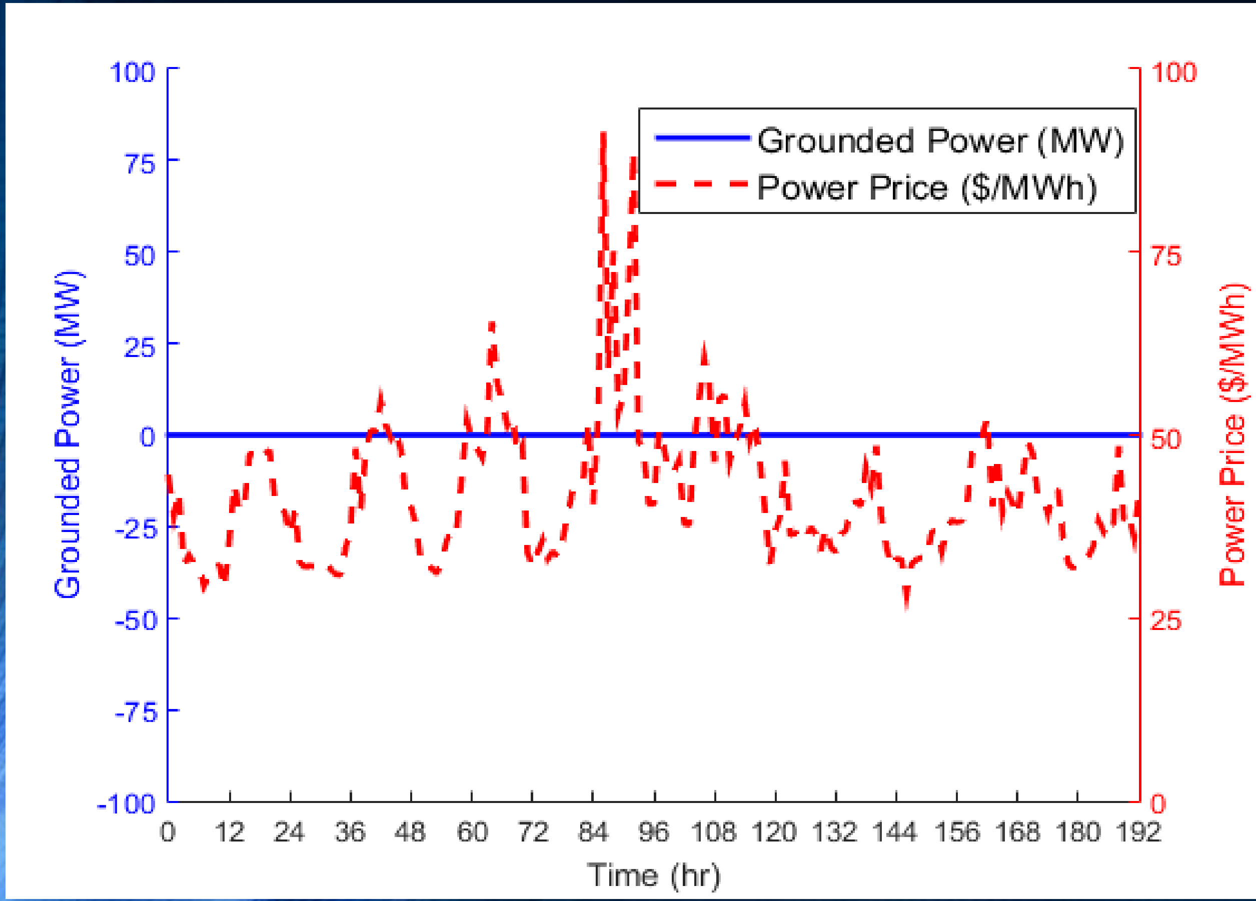
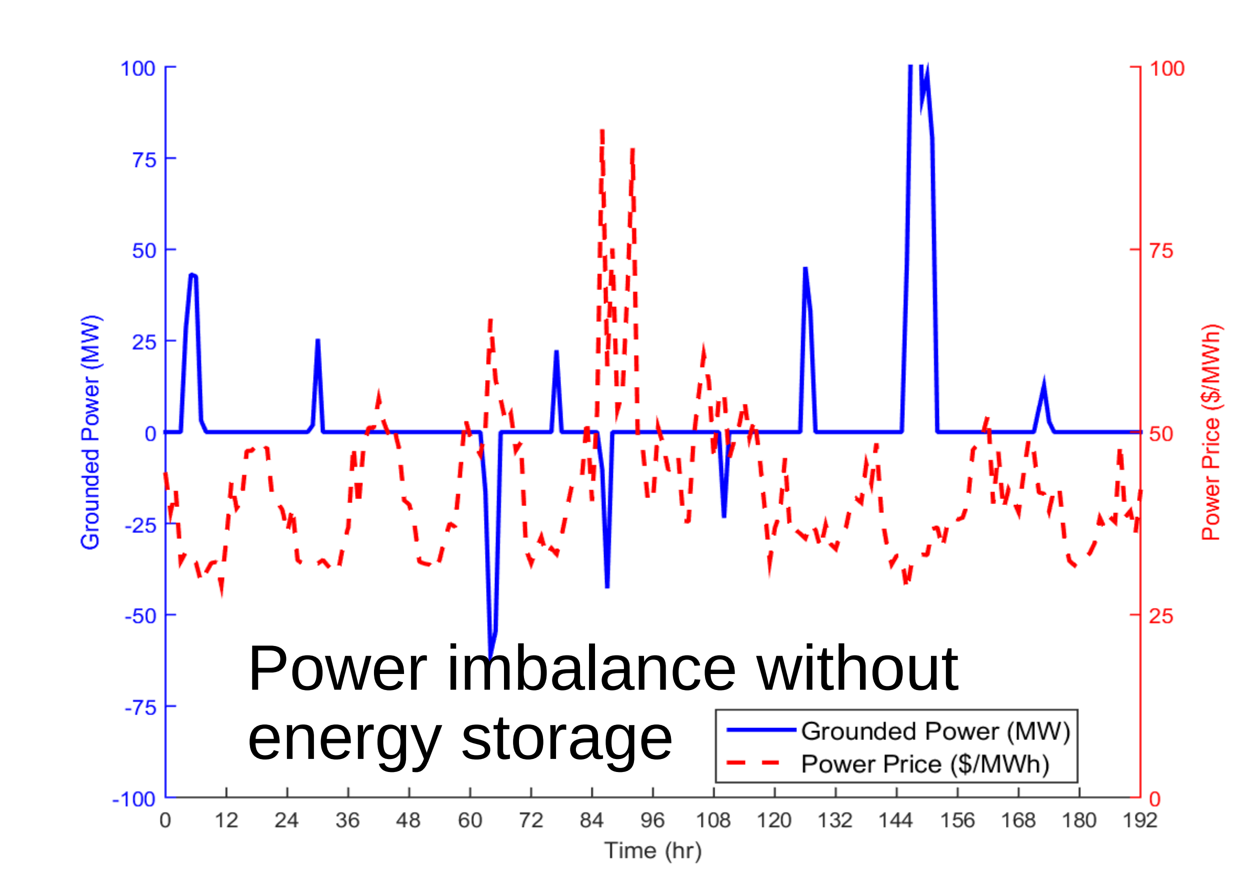
2. Baseline Boiler



# 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

| | With Wind | | Without Wind | |
|---|---|---|---|---|
| | Load-following boiler | Baseline Boiler | Load-following boiler | Baseline Boiler |
| # cycles in Boiler (cost) | 20 ($88200) | 1 ($4410) | 18 ($79380) | 1 ($4410) |
| # cycles in gas turbine (cost) | 17 ($10880) | 21 ($13440) | 23 ($14720) | 15 ($9600) |
| Total cycling costs | $99080 | $17850 | $94100 | $14010 |

- 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

# Acknowledgements

- Sustainable Energy Solutions (SES)

SES INNOVATION

- Graduate students in PRISM Group at BYU


- Undergraduate research assistants

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