Increased Stability of a Power Grid by Energy Storage of Cryogenic Carbon Capture

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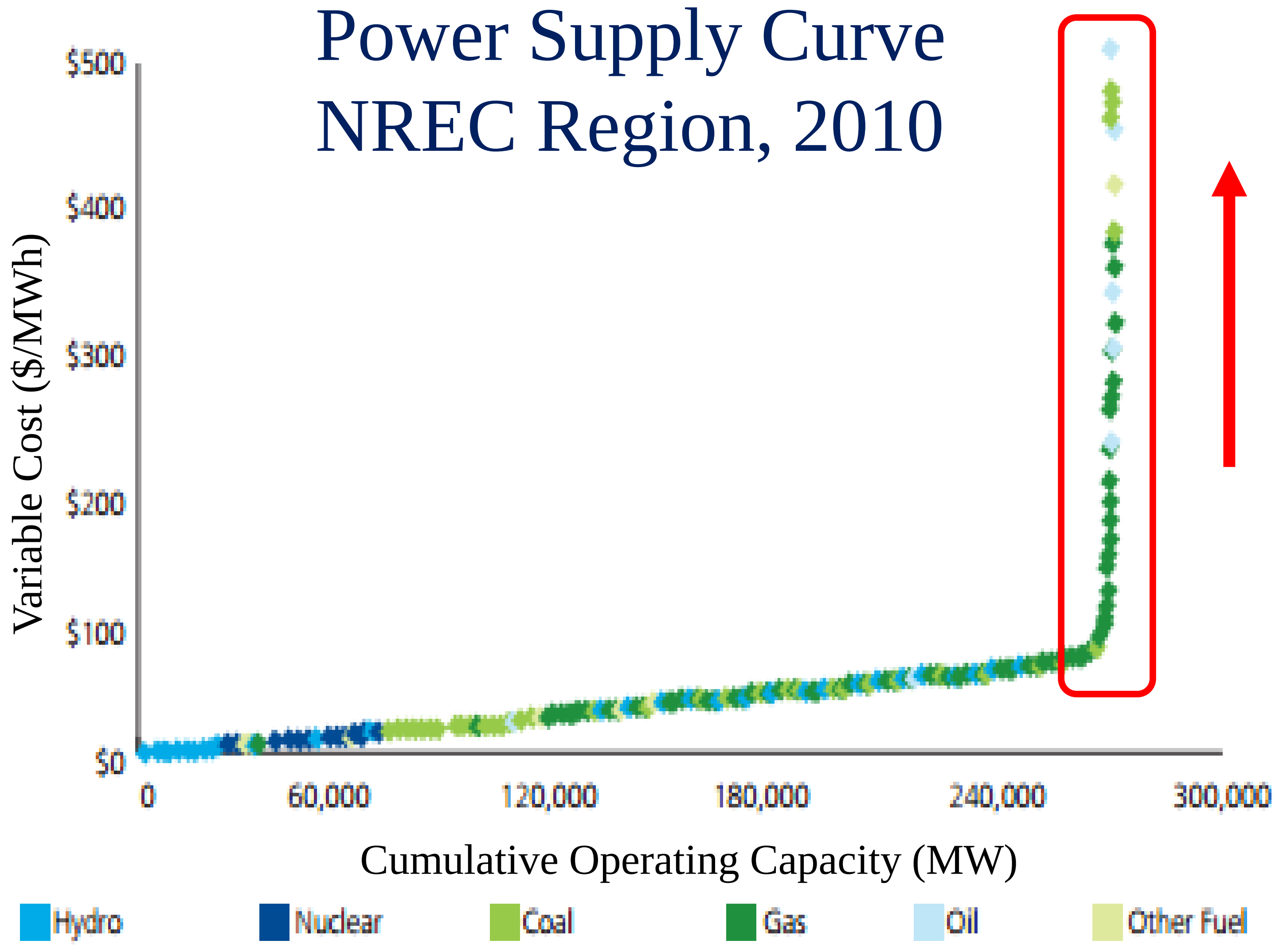
April 2016

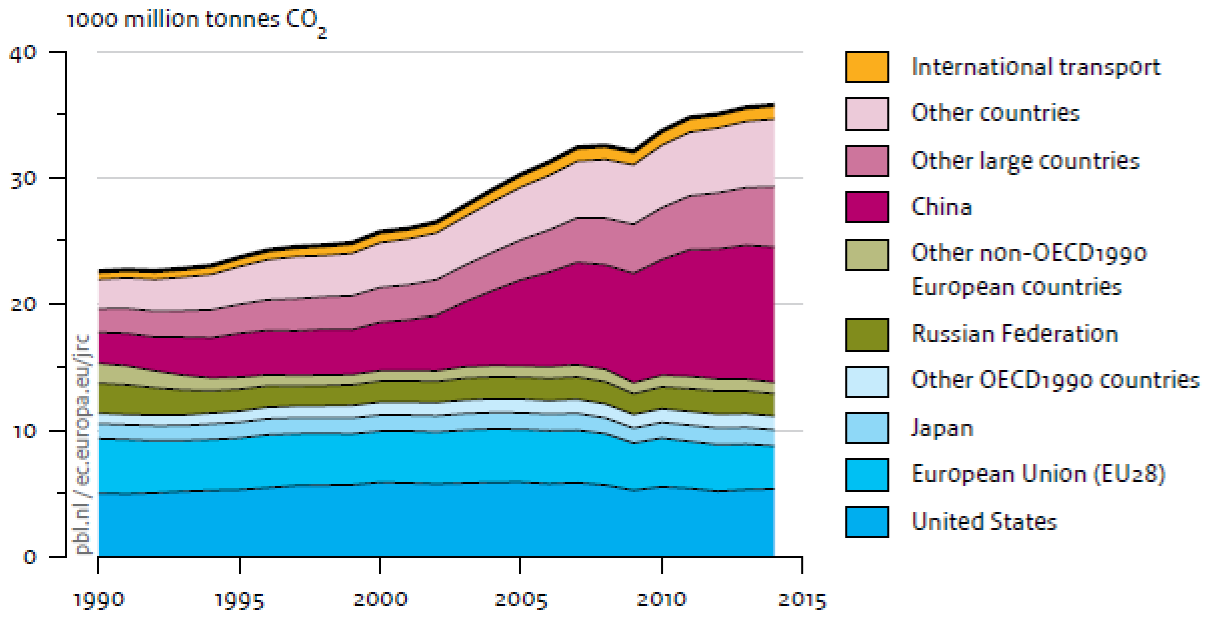
Stability of Power Grid



Low Utilization =
High Cost / MWh

Deloitte Center for Energy Solutions, 2011

CO_2 Capture Systems Impact Grid Stability



Trends in global CO_2 emissions, PBL Netherlands Environmental Assessment Agency, 2015

- New regulations for CO_2 emission from power plants:
  - 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

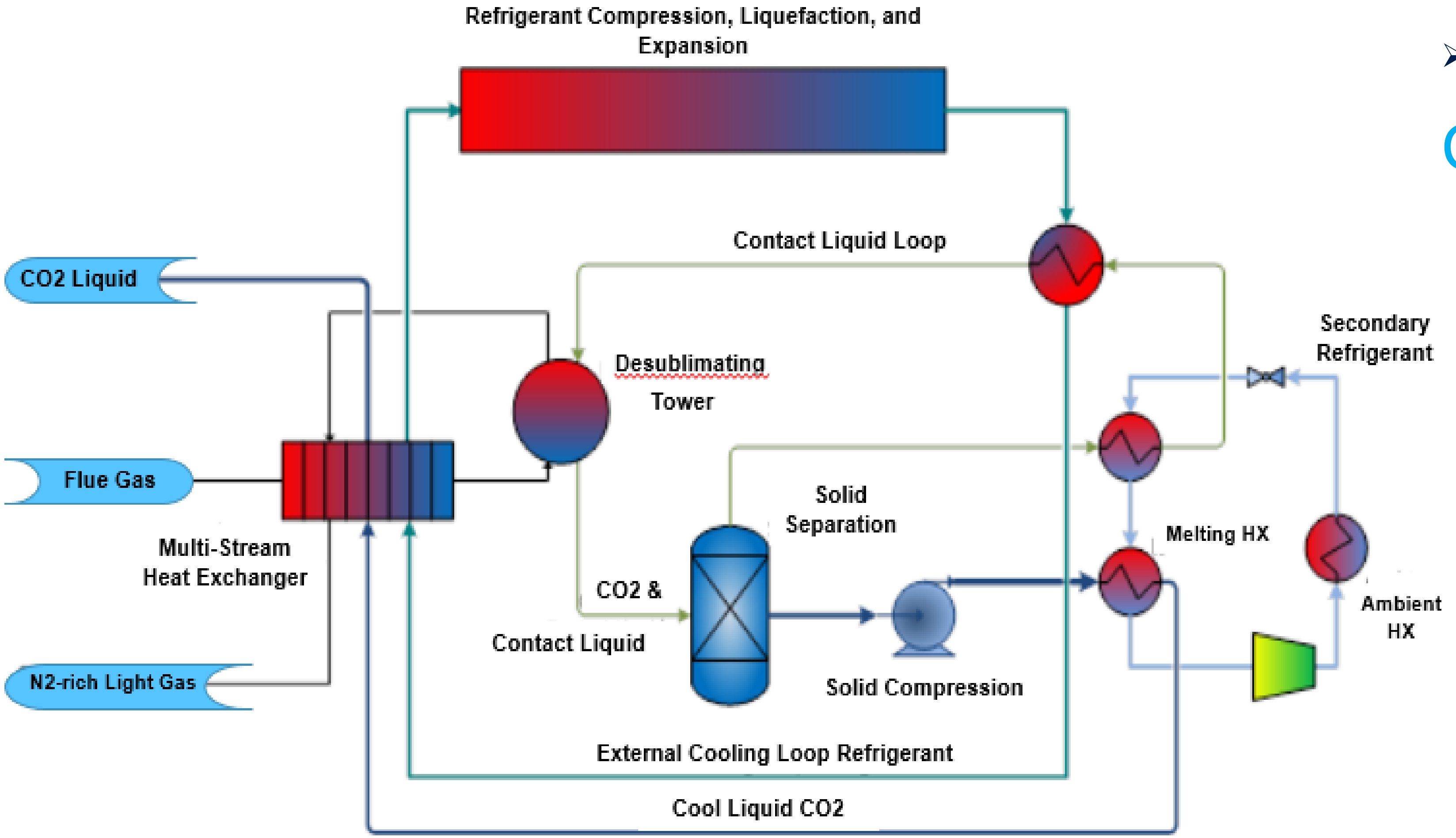
Solutions to Increase Stability

- Advanced Metering Infrastructure
- Demand Response
- Distribution Automation
- Renewable Resource Forecasting
- Distributed Storage (Electric Vehicles with V2G capability and batteries)
- Microgrids (distributed generation)
- Bulk energy storage (Pumped stored hydropower, compressed air energy storage, thermal storage)

Benefits of Energy Storage

- Grid frequency and voltage regulation (grid stabilization and power quality control)
- Shaving of load peaks
- Smoothing of renewable power variability (ramp rate control)
- Energy arbitrage
- Backup power

Cryogenic Carbon Capture (CCC)

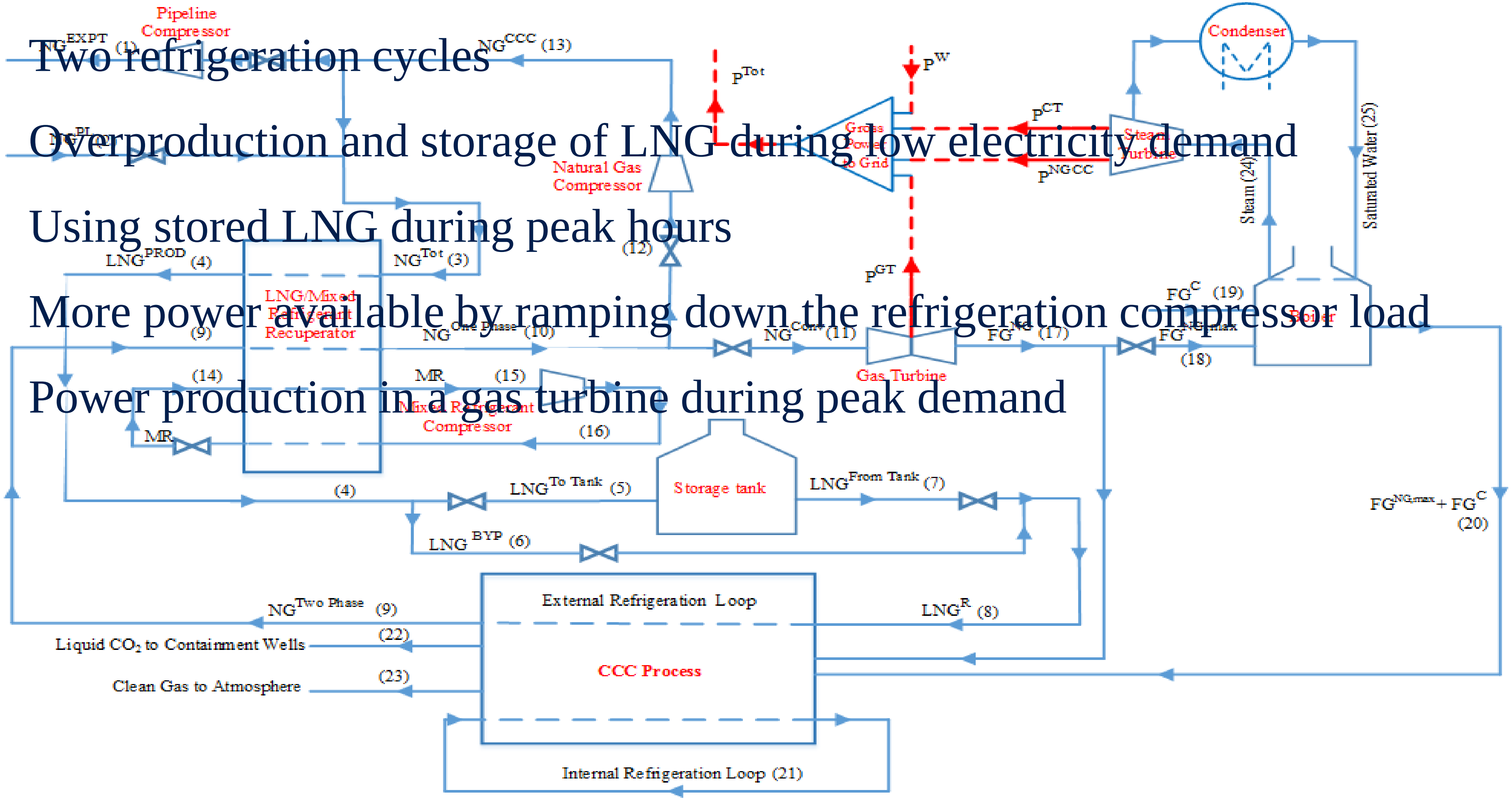


- Advantages of the CCC Process
  - Lower energy consumption
  - Scalable energy storage
  - Rapid-load-change
  - capability
  - Flexible operation
  - Energy recovery

Jensen, PhD Dissertation, Brigham Young University, 2015

Hybrid System of Power Generation and CCC

- Two refrigeration cycles
- Overproduction and storage of LNG during low electricity demand
- Using stored LNG during peak hours
- More power available by ramping down the refrigeration compressor load
- Power production in a gas turbine during peak demand



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Improved Profitability through Integration

- Dynamic integration of CCC with power generation units
- Assumed 90% CO_2 capture rate
- Meet residential and CCC electricity demands
- Maximize operational profit of the hybrid system
- Minimize cycling of the coal power plant

Optimization Approach

- Objective function: ℓ1-norm

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

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

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

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

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

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

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

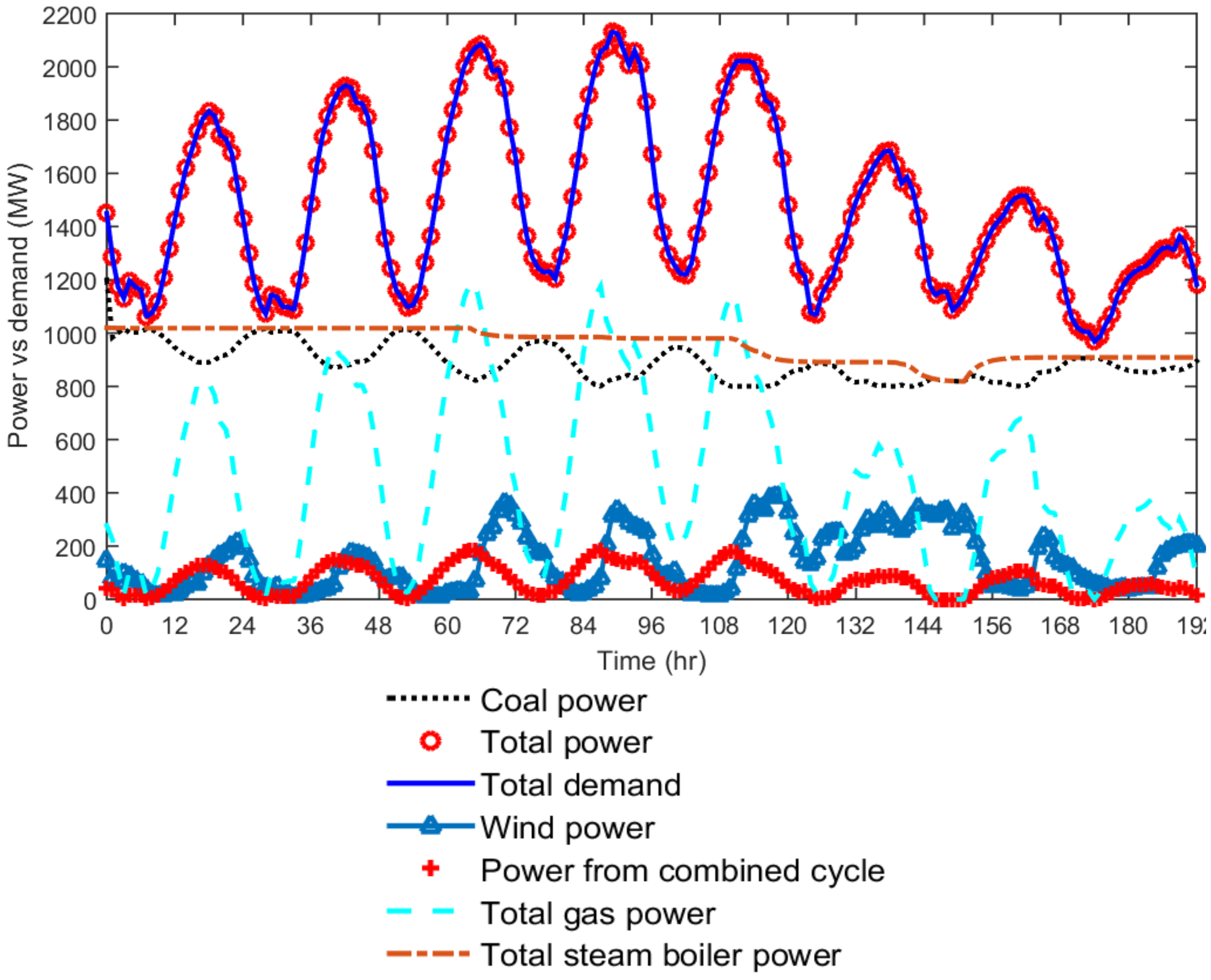
$$e_{lo} \geq \left(y_{t,lo} - y_m\right)$$

- Dead-band for the controlled variable
- Prioritize multi-objective functions
- Orthogonal collocation on finite elements for DAE to NLP conversion
- Active Set or Interior Point Solvers
  - APOPT or IPOPT
- APMonitor Modeling Language

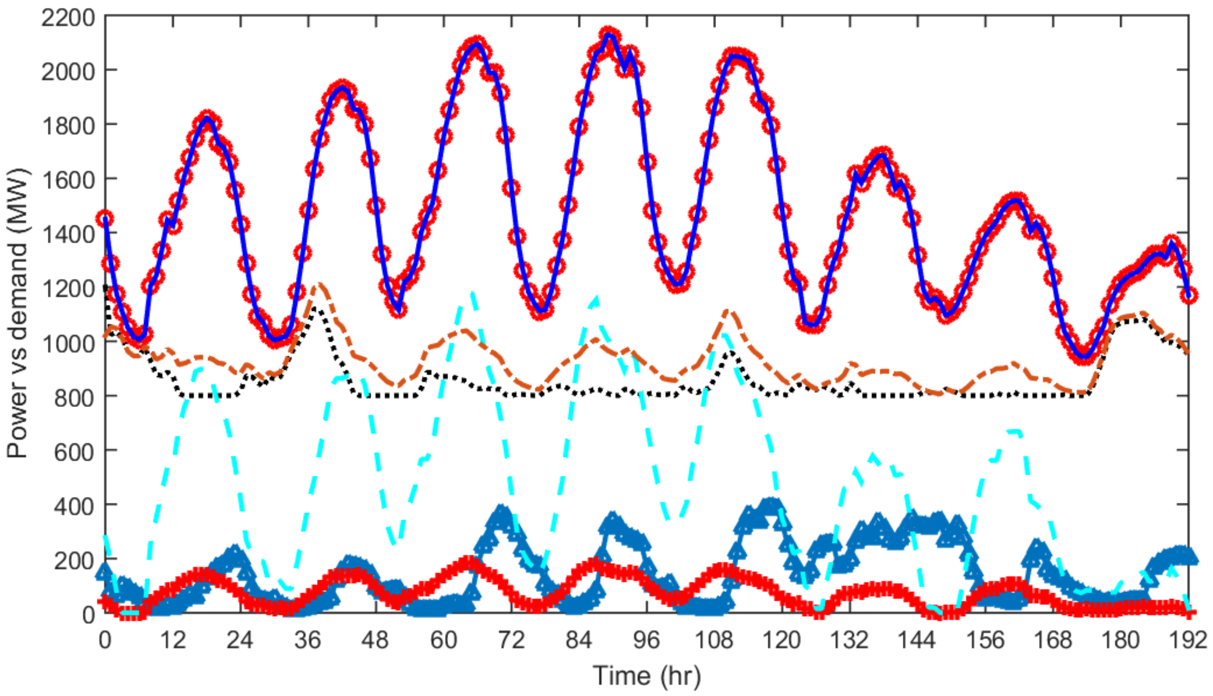
Power Production vs. Electricity Demand

PRISM

Baseline Boiler



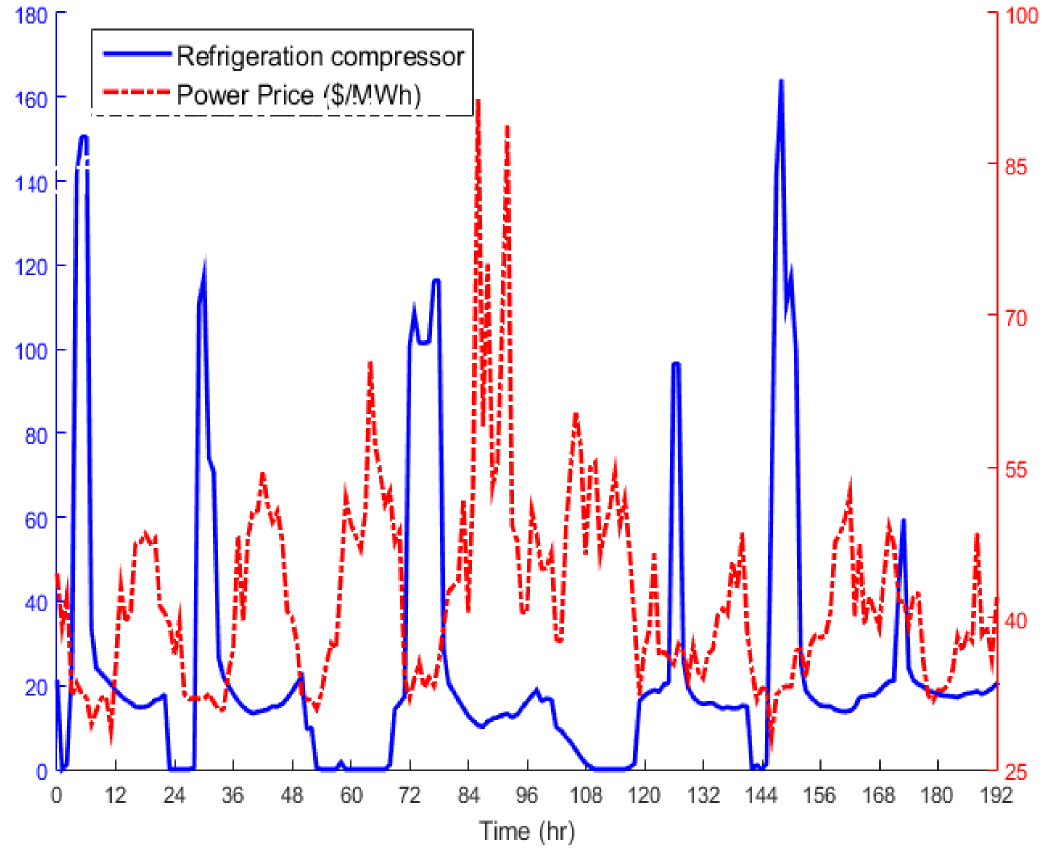
Load-following Boiler



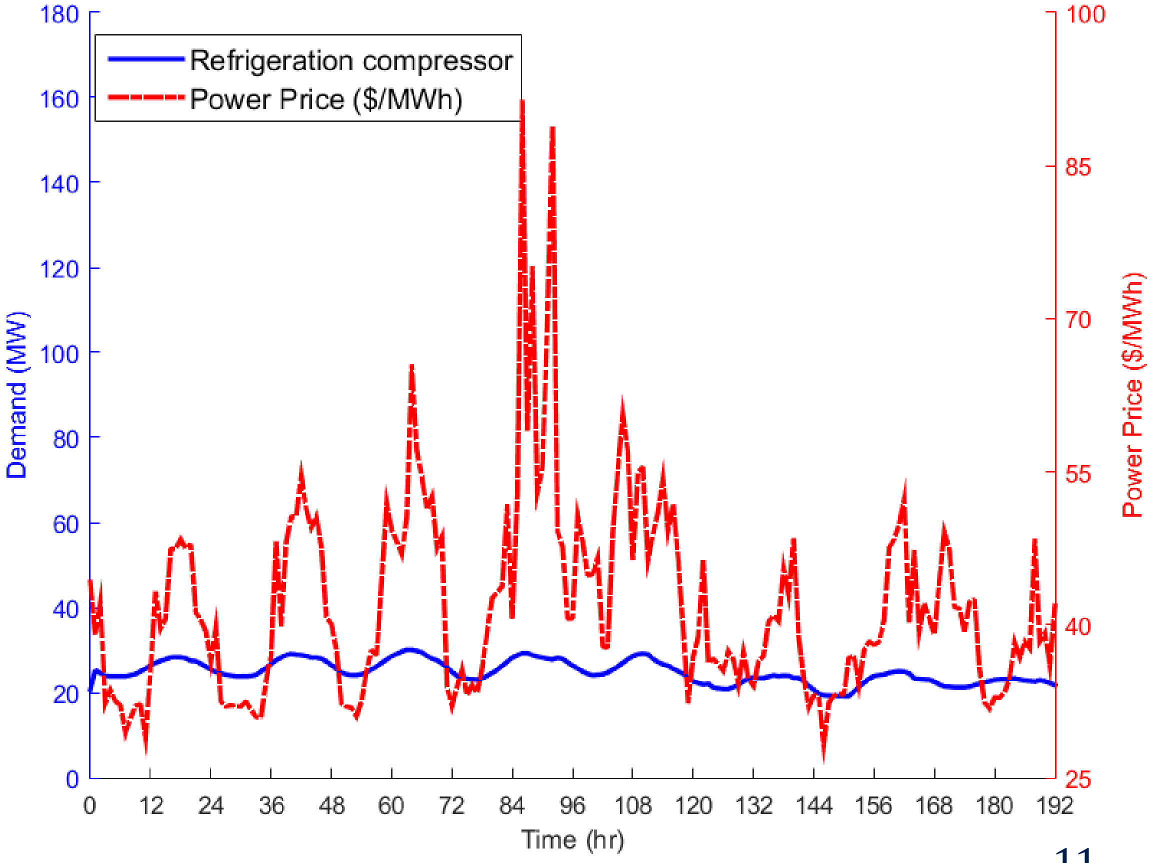
- Meet the total electricity demand
- Refrigerant storage used in gas turbine
- 100% utilization of the wind power

Impact of Energy Storage on Baseline Case

With Energy Storage & Combined Cycle Power Production



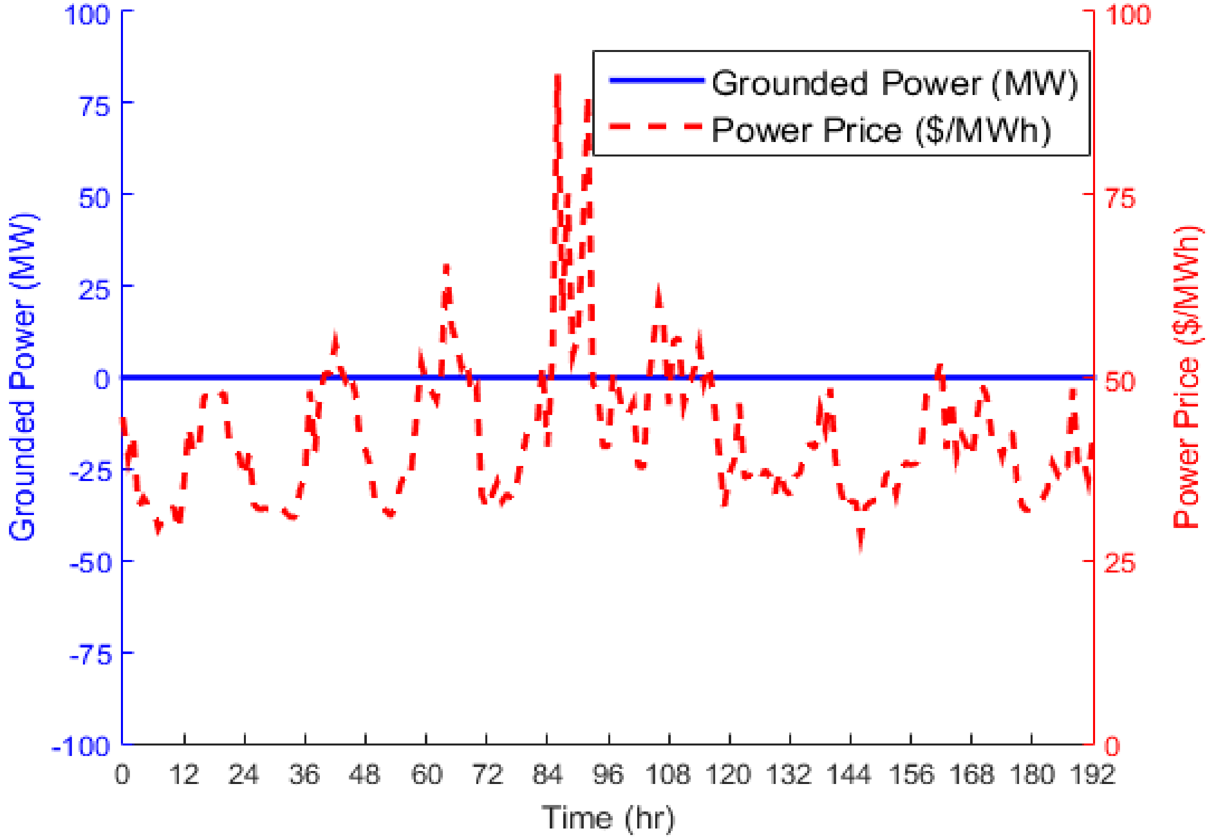
Without Energy Storage & Simple Cycle Power Production



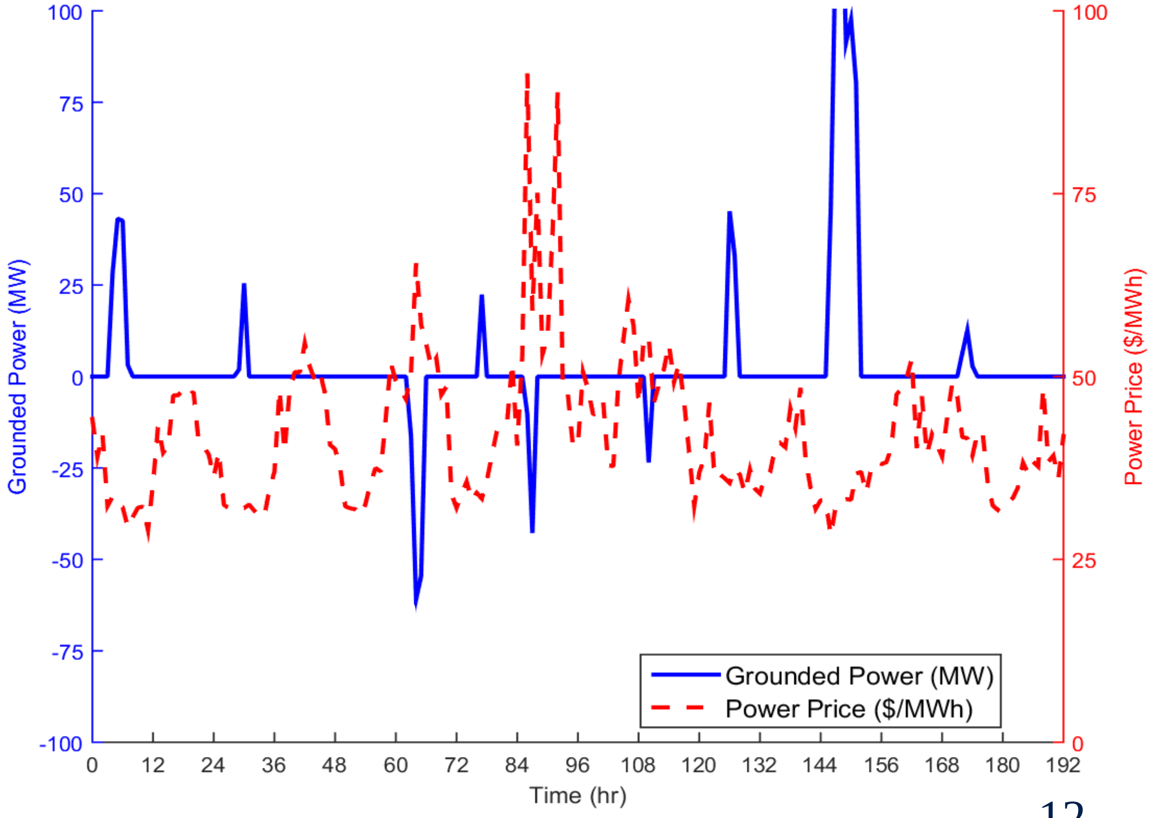
Comparison of Power Production

$$Grounded\ Power = Total\ Power\ - Total\ Demand$$

With Energy Storage & Combined Cycle Power Production



Without Energy Storage & Simple Cycle Power Production



Profitability

- $13.6k/hr average profit
- $58k/hr average hourly revenue
- Recovery of most of the CCC constructional expenses by taking advantage of the arbitrage of energy

Cycling Cost

- Increased thermal, pressure, and mechanical related stress and fatigue

- Cycling scenarios: Cold start, Hot start, Warm start, and Load-following

Cycling Cost (Continued)

- Rainflow cycle counting algorithm

	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

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%
- Reduction in the need to spinning reserves
- Power grid stability

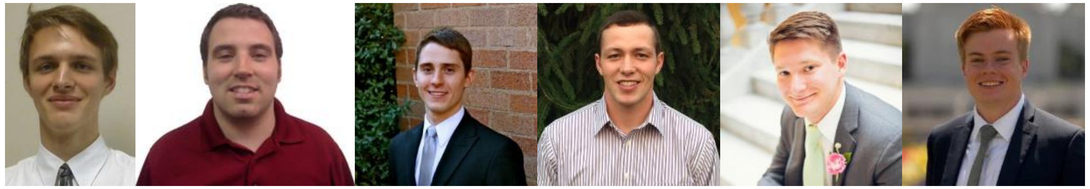
Acknowledgements

- Sustainable Energy Solutions (SES)

SES INNOVATION

- Graduate students in PRISM Group at BYU

- Undergraduate research assistants



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