Price Responsive Demand for Operating Reserves in Co-Optimized Electricity Markets with Wind Power

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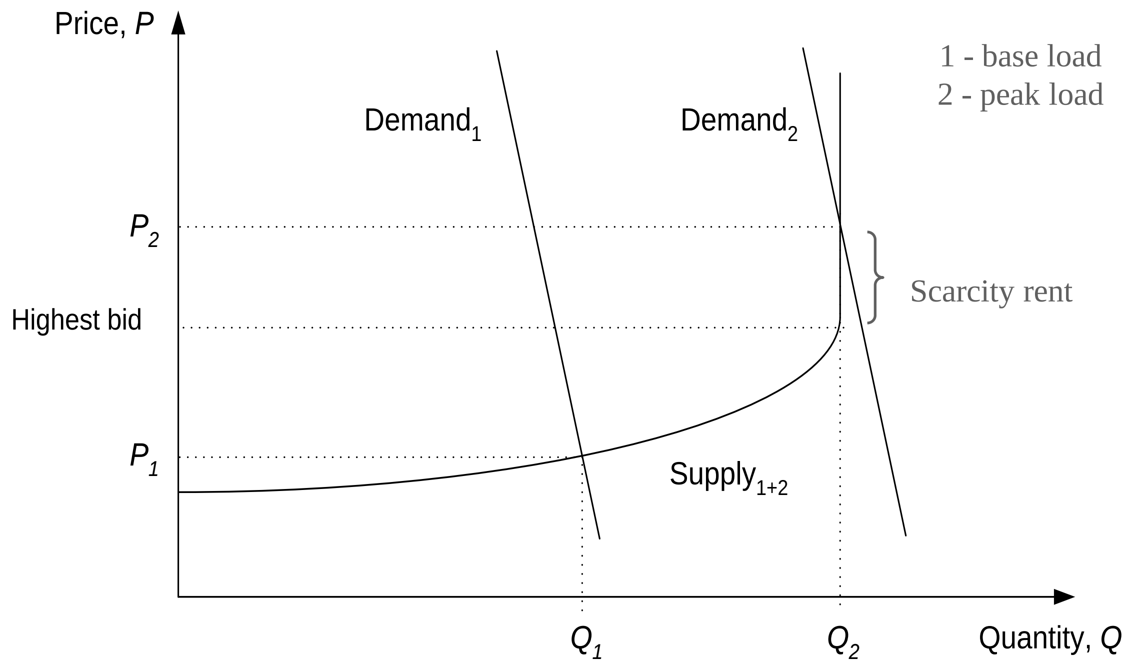
Outline

- Background and Motivation
  - Scarcity pricing in electricity markets
  - Wind power uncertainty in market operations
- Analytical approach
  - Wind power forecast uncertainty
  - Demand curve for operating reserves
  - Market operations: commitment and dispatch
- Case study of IL power system
  - Assumptions
  - Costs, prices, revenue
- Concluding Remarks

Prices and Investments in the Electricity Market

In a perfect market:

- Scarcity rent covers investment costs for the optimal mix of new generation
- Investments should come in time to meet demand



Source: Botterud 2003

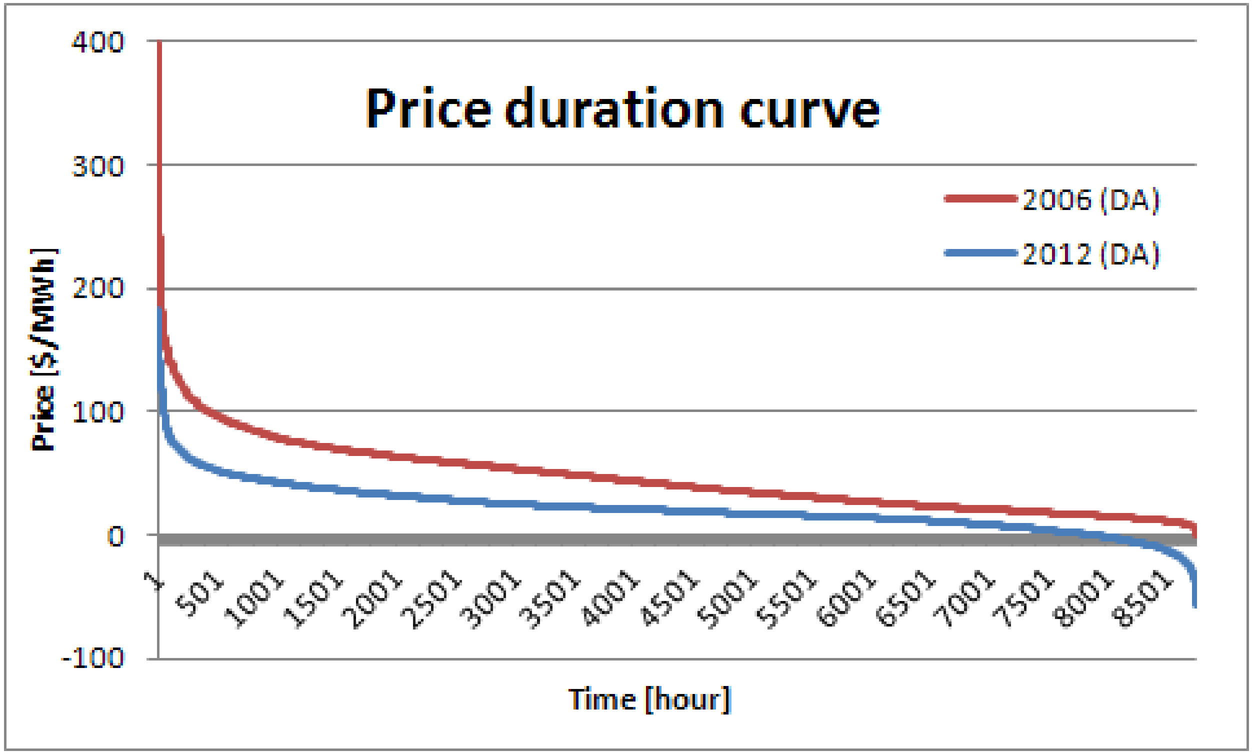
Potential problems for adequate generation investments:

- Limited demand response, price caps and poor scarcity pricing ("missing money"), high investment risks difficult to hedge, market power
- *How does a large-scale wind power expansion influence investments?*

  - Resource variability and ramping, forecast uncertainty, low marginal costs

Electricity Prices in MISO node 2006 and 2012

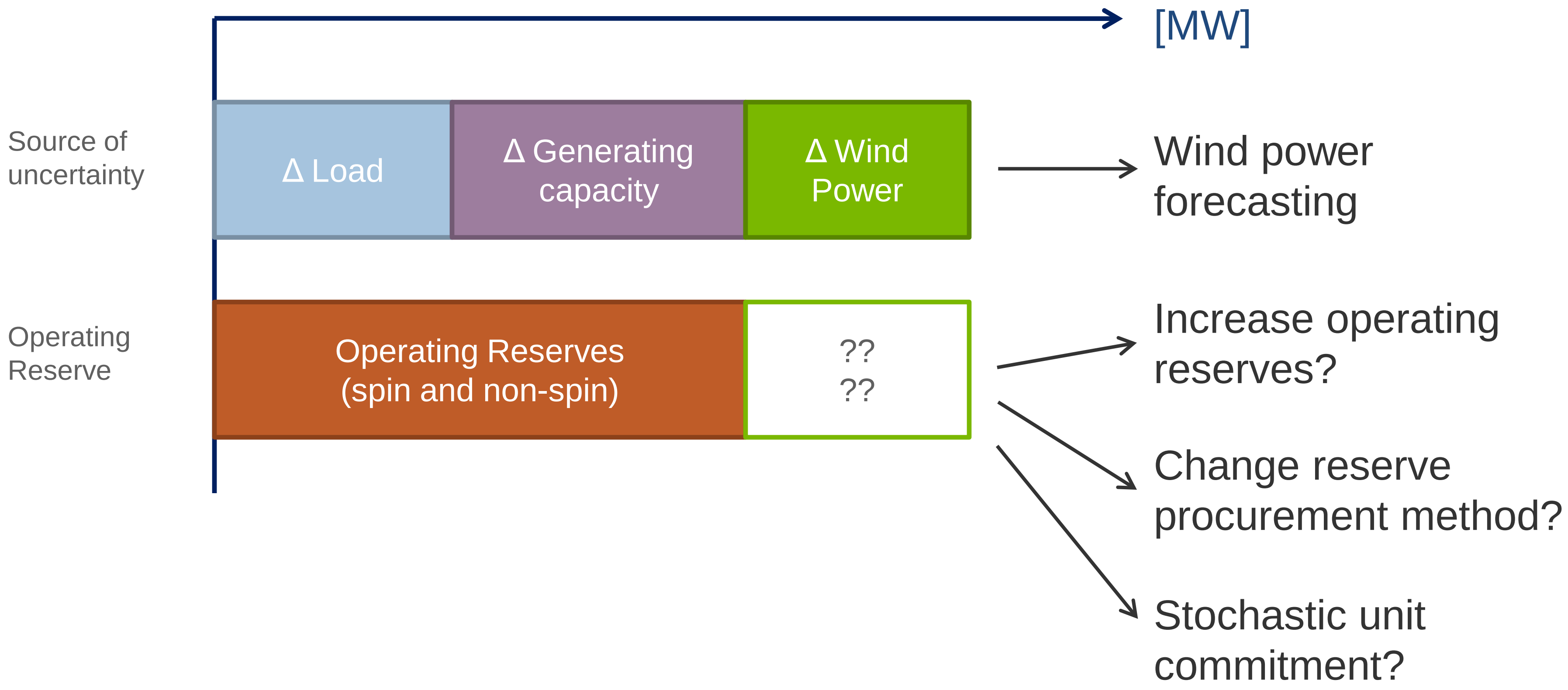
- Historical day-ahead prices for ALTW.FOXLK1 node in Lakefield, MN



Price	2006	2012
Average [$/MWh]	46.1	21.3
Rel. St.Dev. [%]	64.0	92.3

Wind power increases the need for adequate scarcity pricing

Handling Uncertainties in System/Market Operation



A <u>demand curve for operating reserves</u> can address forecast uncertainty in short-term operations and improved scarcity pricing for long-term resource adequacy

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Probabilistic Forecasting - Kernel Density Estimation

- Conditional wind power probabilistic forecasting

$$f_P\left(p_{t+k} \mid X = x_{t+k|t}\right) = \frac{f_{P,X}\left(p_{t+k}, x_{t+k|t}\right)}{f_X\left(x_{t+k|t}\right)}$$

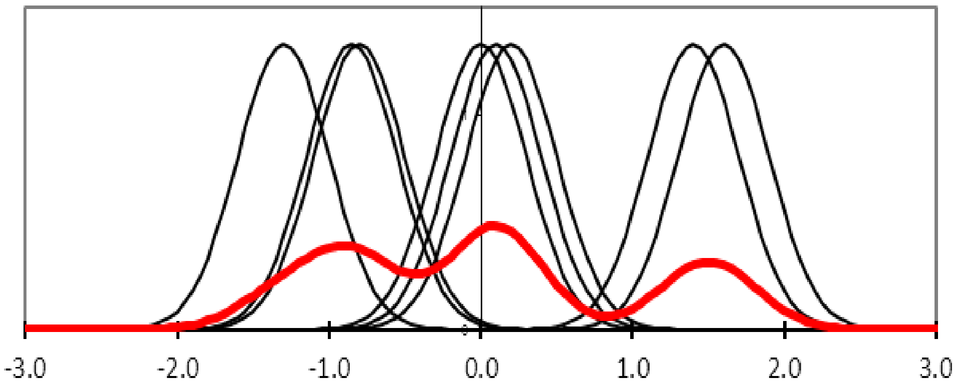
Joint or multivariate density function of *p* and *x* (numerator)

Marginal density of *x* (denominator)

- Kernel density estimation (KDE)
  - Advantages
    - Forecasts the full probability density function
    - Nonparametric
  - Example

$$\hat{f}_X(x) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{h_i} \cdot K\left(\frac{x - X_i}{h}\right)$$

$$K(x) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{\sqrt{2\pi}} \cdot e^{-\frac{(x-X_i)^2}{2 \cdot h^2}}$$



Probabilistic Forecasting - Quantile-Copula Estimator

Copula Definition

$$F_{XY}(x,y) = C(F_X(x), F_Y(y))$$

multivariate distribution function separated in:
- marginal functions
- dependency structure between the marginals modeled by a copula

copula density function

$$f(x,y) = \frac{\partial^2}{\partial u \cdot \partial v} \cdot C(u,v) = f_X(x) \cdot f_Y(y) \cdot c(u,v)$$

$$f(y|X=x) = \frac{f_X(x) \cdot f_Y(y) \cdot c(u,v)}{f_X(x)} = f_Y(y) \cdot c(u,v)$$

KDE ESTIMATOR

$$\hat{c}(u,v) = \frac{1}{N}\sum_{i=1}^{N} K\left(\frac{u-U_i}{h_u}\right) \cdot K\left(\frac{v-V_i}{h_v}\right)$$

KDE ESTIMATOR

$$\hat{f}_Y(y) = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{h_i} \cdot K\left(\frac{y-Y}{h_y}\right)$$

empirical cum. dist.

$U_i = F_X^e(X_i)$ and $V_i = F_Y^e(Y_i)$

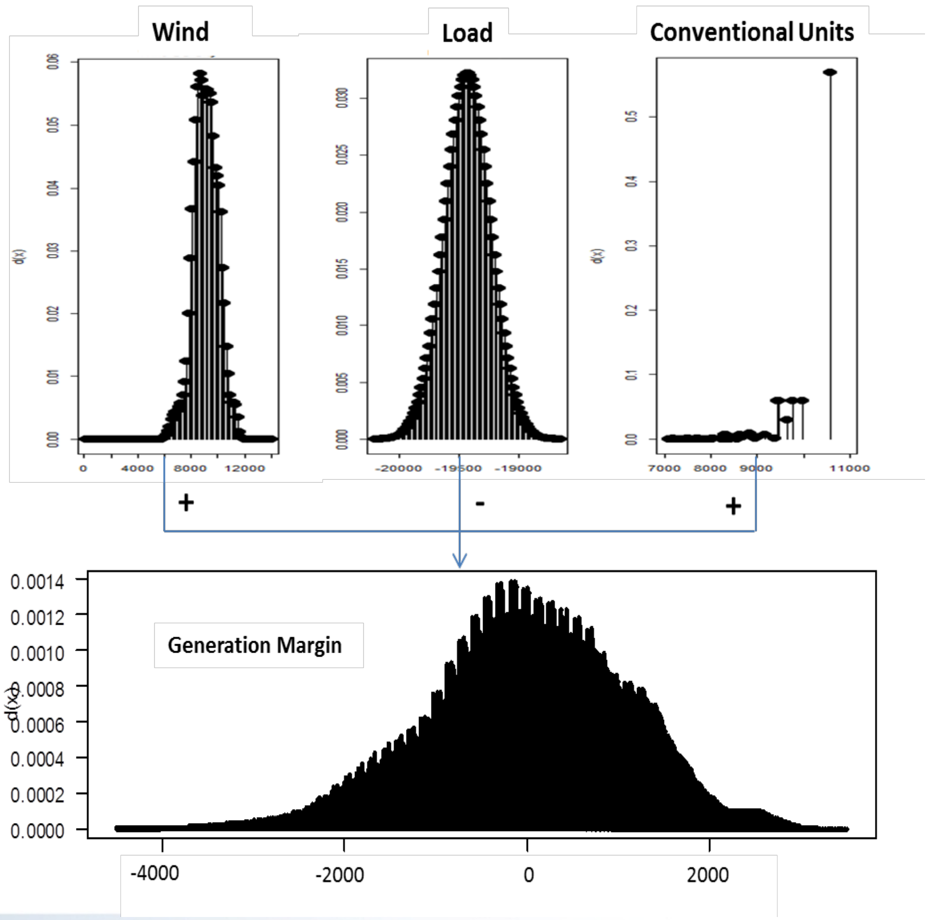
$$F^E(t) = \frac{1}{N} \cdot \sum_{i=1}^{N} I(x_i \le t)$$

$$\hat{f}(y|X=x) = \frac{1}{N \cdot h_y} \cdot \sum_{i=1}^{N} K_y\left(\frac{y-Y_i}{h_y}\right) \cdot \frac{1}{N} \cdot \sum_{i=1}^{N} K_u\left(\frac{F_X^e(u) - F_X^e(U_i)}{h_u}\right) \cdot K_v\left(\frac{F_X^e(v) - F_X^e(V_i)}{h_v}\right)$$

[Bessa et al. 2012]

Demand Curve for Operating Reserves – Overview

- Basic idea
  - Consider the uncertainties from load and supply (thermal and wind)
  - Estimate the risk of supply shortage for system
  - Link the expected cost of this risk to the price to pay for reserves (Hogan, 2005)

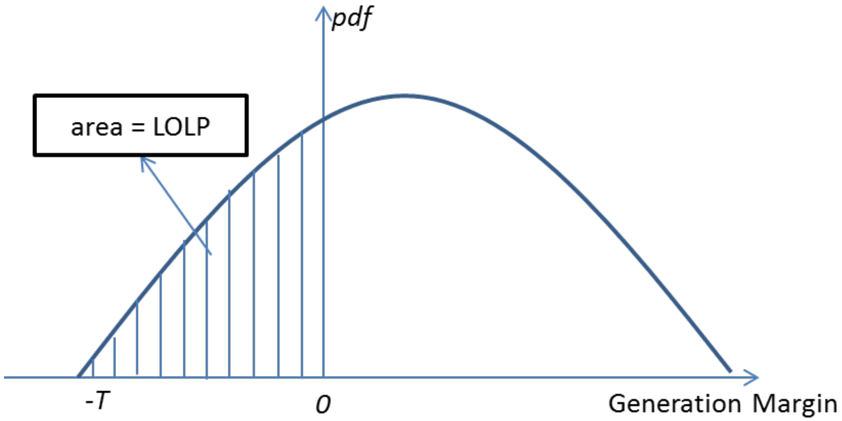


- Uncertainty sources:
  - Wind power: probabilistic forecast
  - Load: forecasting error
  - Thermal units: forced outage rates

From Generation Margin to Demand Curve

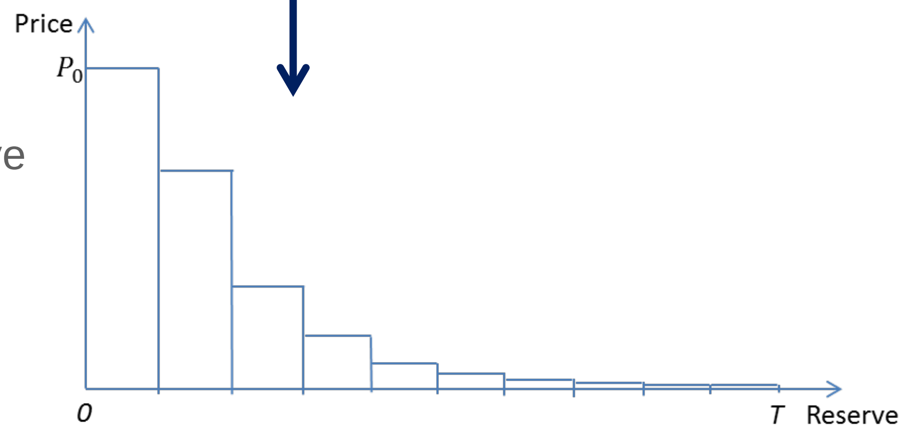
LOLP: Loss of load probability
VOLL: Value of loss load

Generation Margin Distribution



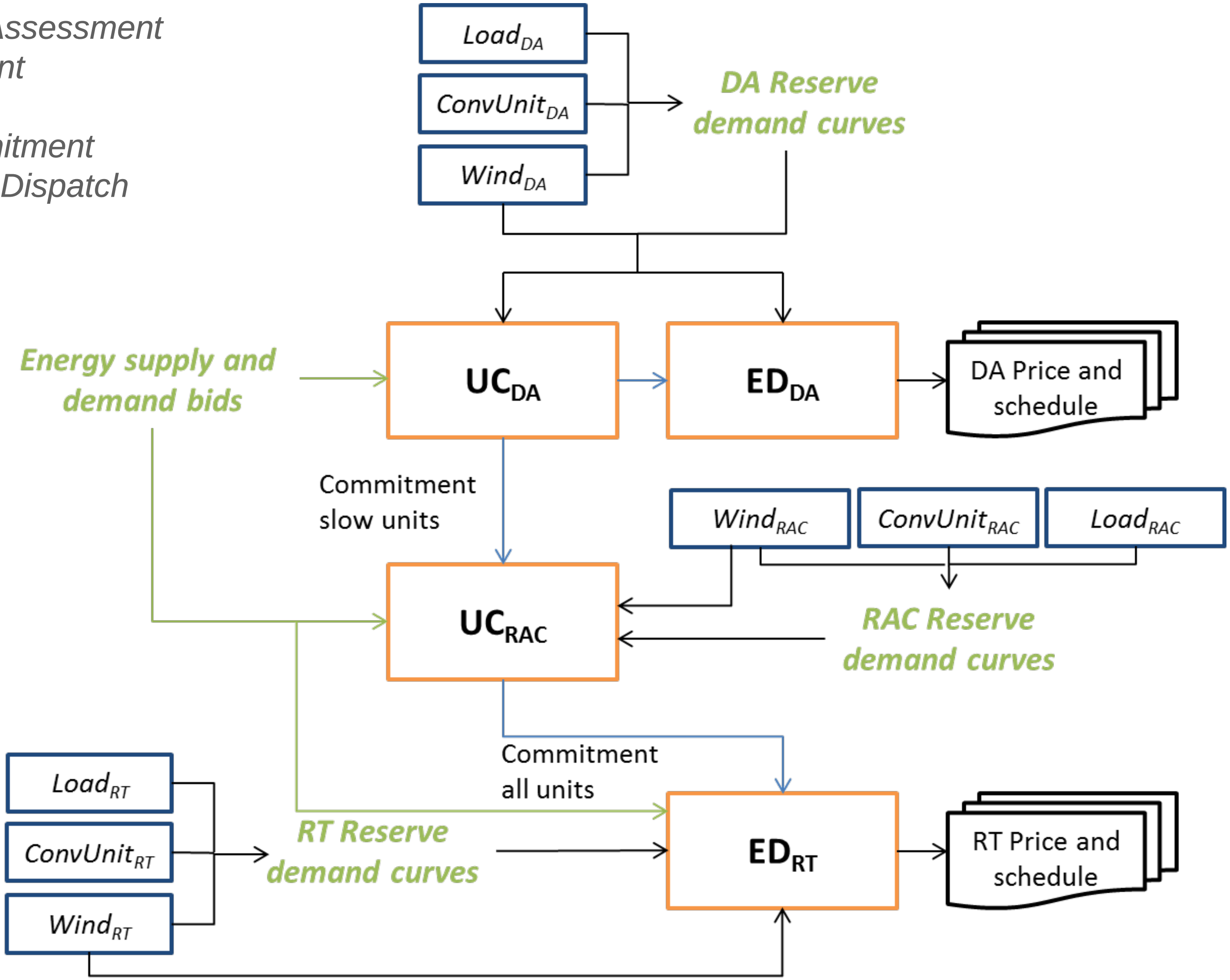
*Price(reserve) = LOLP(reserve,gen.margin) * VOLL*

Stepwise Operating Reserve Demand Curve



Simulating Electricity Market Operations

DA: Day-ahead
RAC: Reliability Assessment Commitment
RT: Real Time
UC: Unit Commitment
ED: Economic Dispatch



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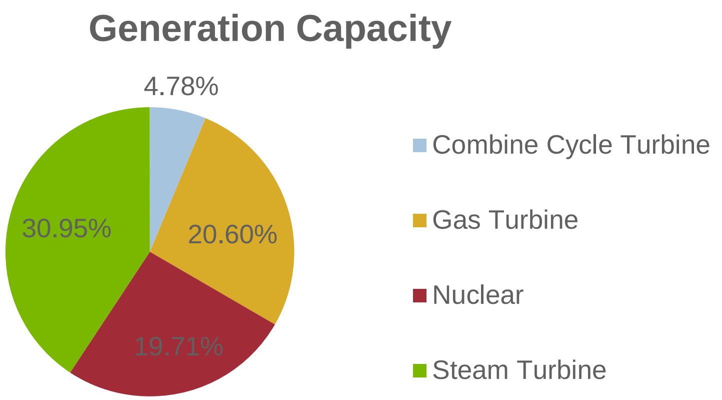
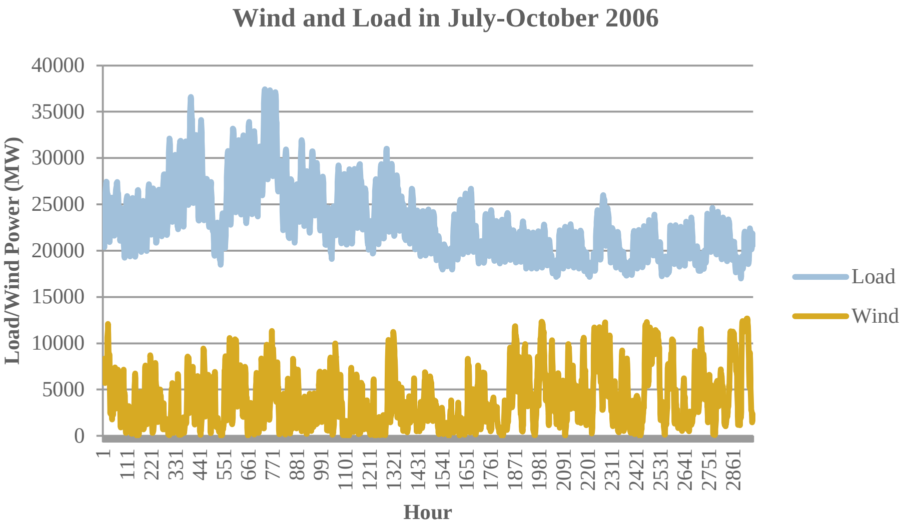
Case Study Assumptions

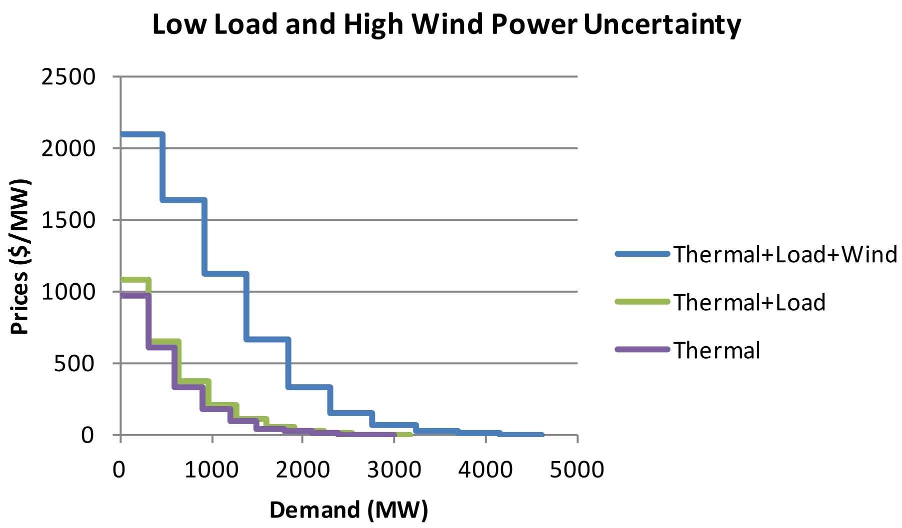
- **210 thermal units: 41,380 MW**
  – Base, intermediate, peak units
- **Peak load: 37,419 MW**
  – 2006 load series from Illinois
- **Wind power: 14,000 MW**
  – 2006 wind series from 15 sites in Illinois (NREL EWITS dataset)
  – 20% of load
- **Simulation periods**
  (1) High load period (July); (2) Low load period (Oct)
- **Curtailment assumptions**
  - Value of Lost Load: $3500/MWh
  - Value of operating reserve shortfall: $1100/MWh

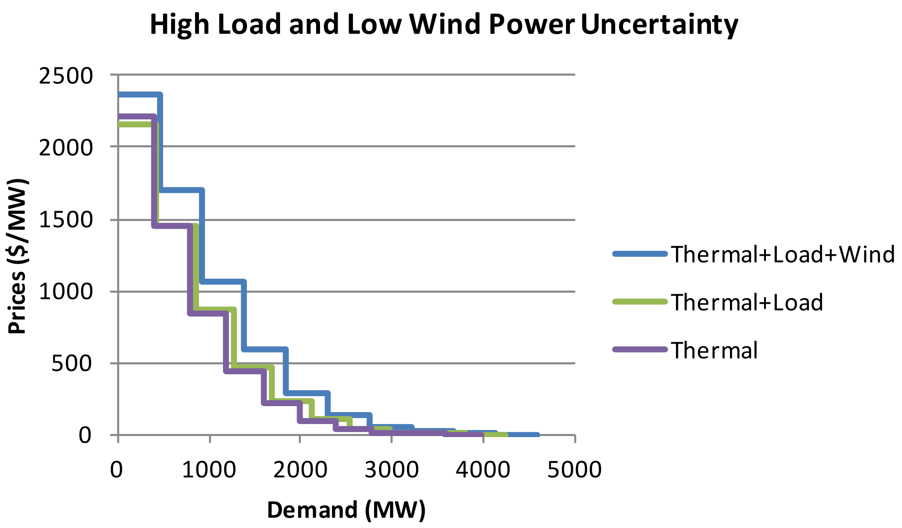




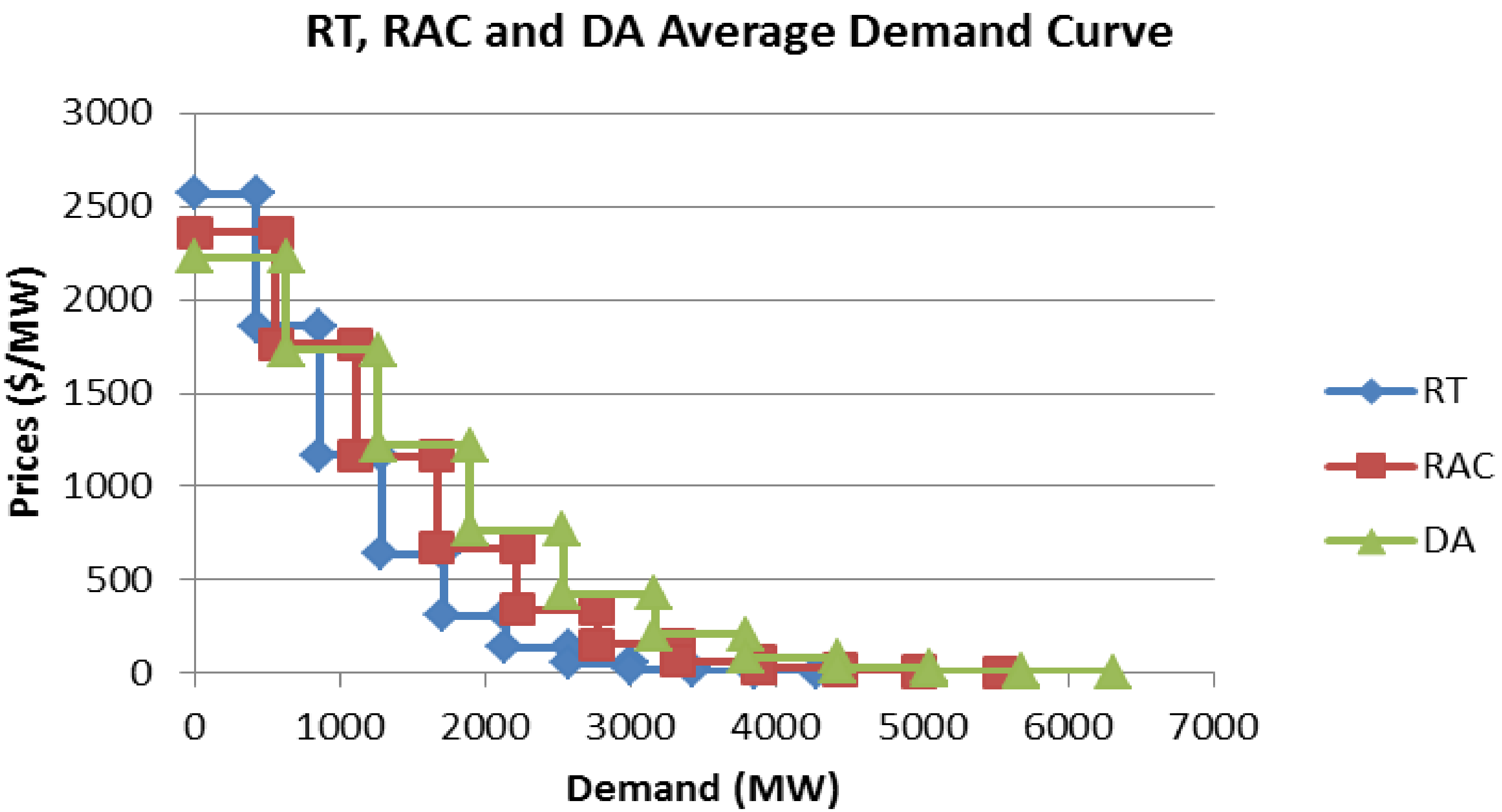
Demand for Operating Reserves is Dynamic

- Demand curve examples
  - Hourly demand curves for the sum of spinning and non-spinning reserves
  - Contributions to reserve demand for two selected hours:





Average OR Demand in July

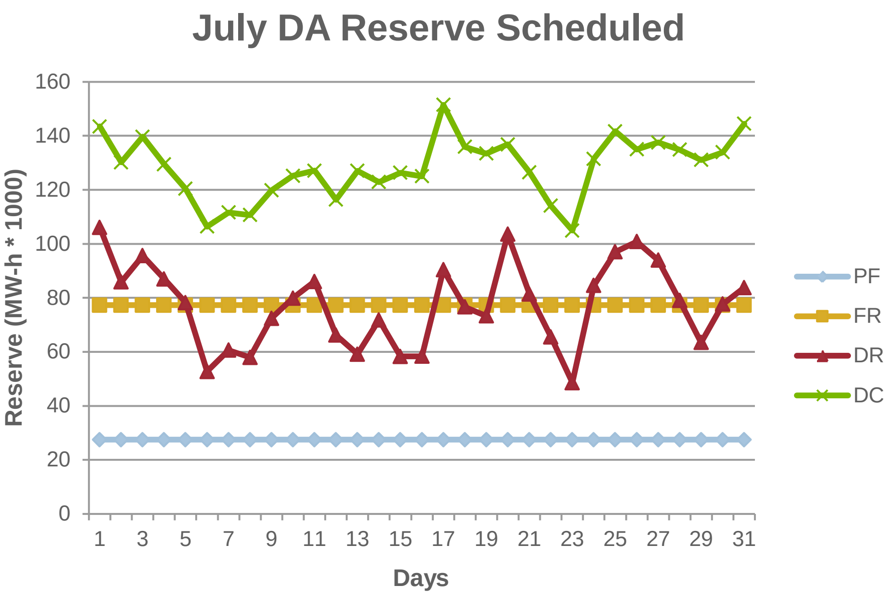


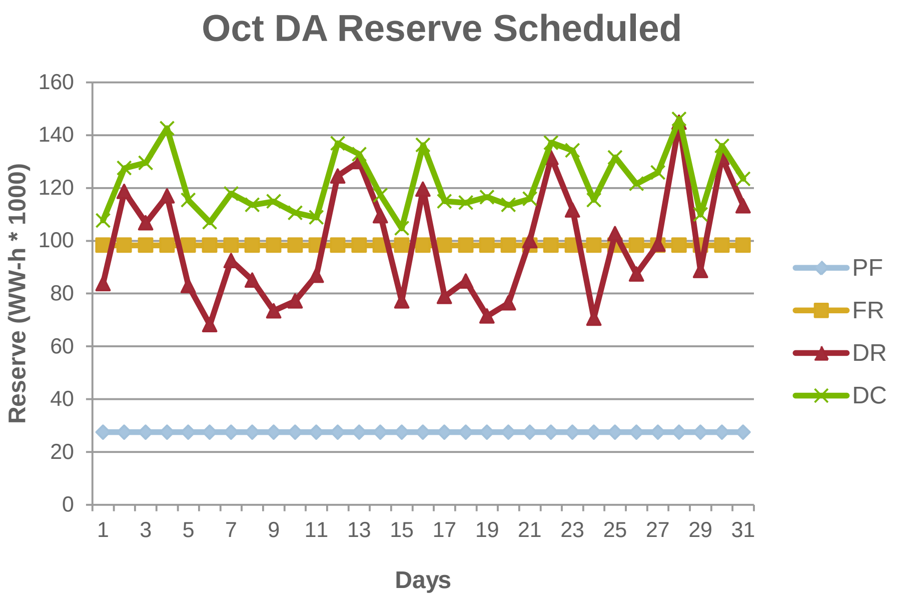
- Total demand for reserves is higher in DA than in RAC and RT.

Simulated Cases

Case	Description	Wind power forecast	Operating reserves		
			Generator contingency	Load forecast error	Wind forecast error
PF	Perfect forecast	Perfect	1146 MW	No	No
FR	Fixed reserve	50 % quantile	1146 MW	No	Avg. 50-1 quant.
DR	Dynamic reserve	50 % quantile	1146 MW	No	50-1 quant.
DC	Demand curve	50 % quantile	Joint demand curve		

Impact on Operating Reserves Schedule

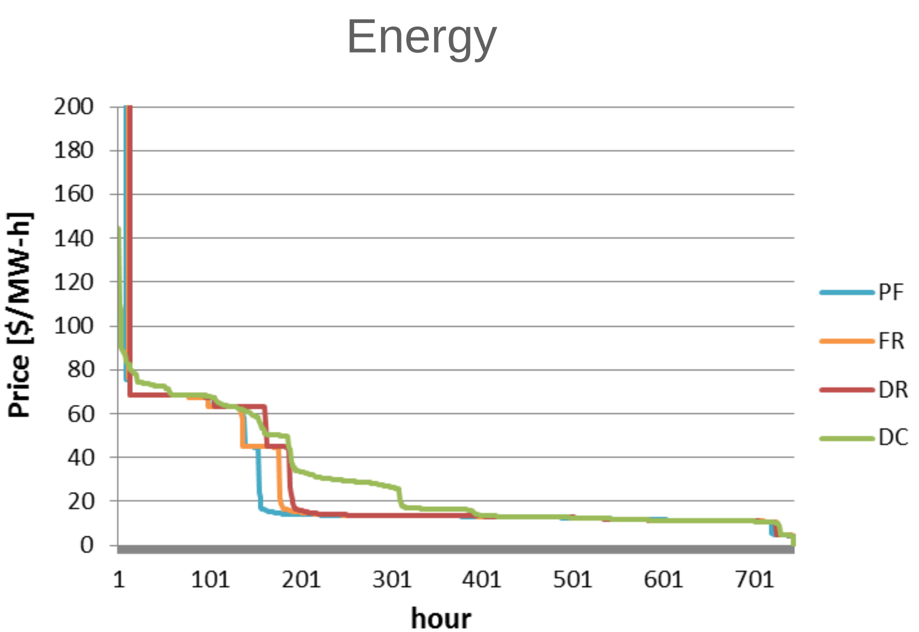


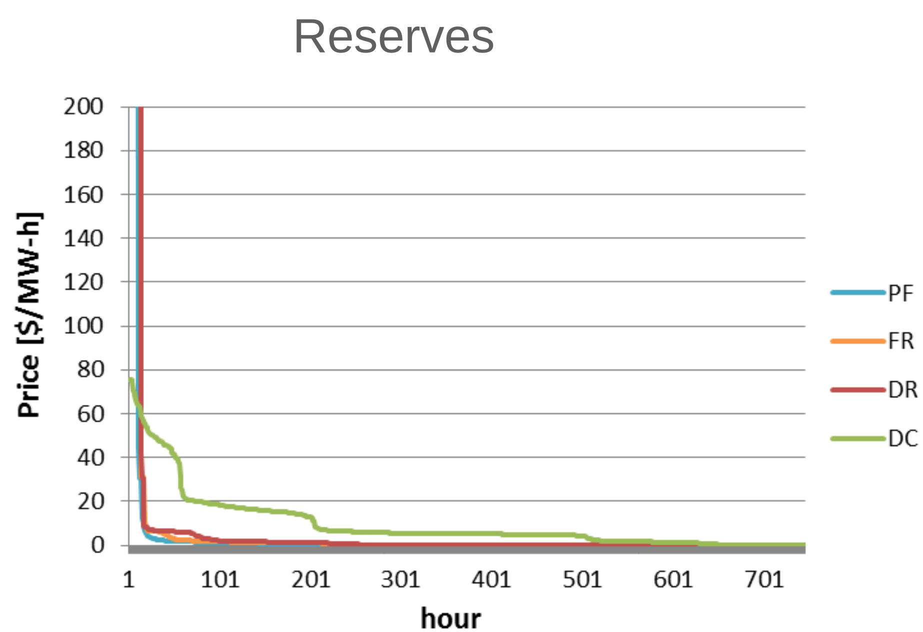


- The demand curve tends to schedule more operating reserves

Implications for Energy and Reserves Prices

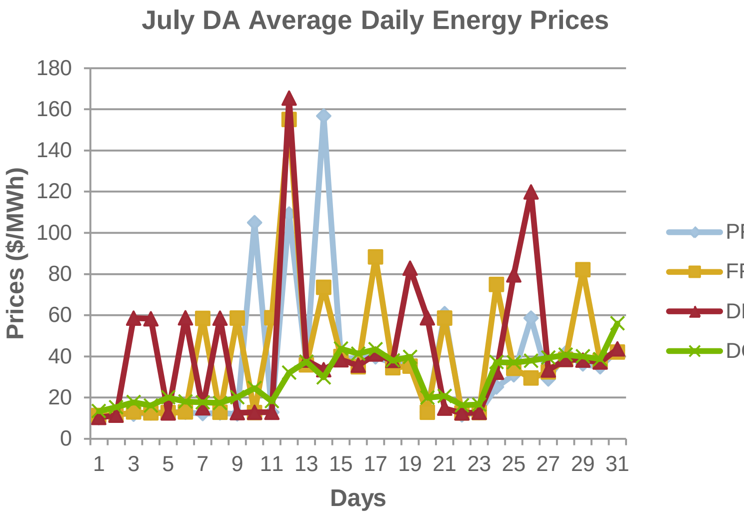
- Price duration curves for day-ahead market, month of July:

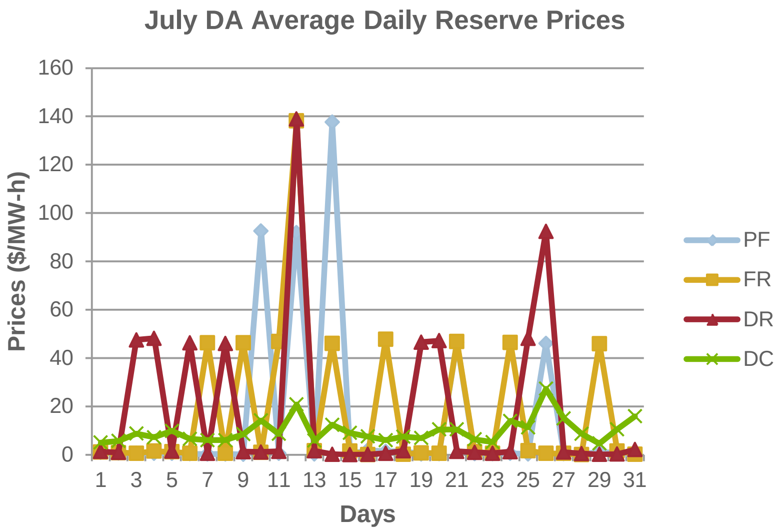


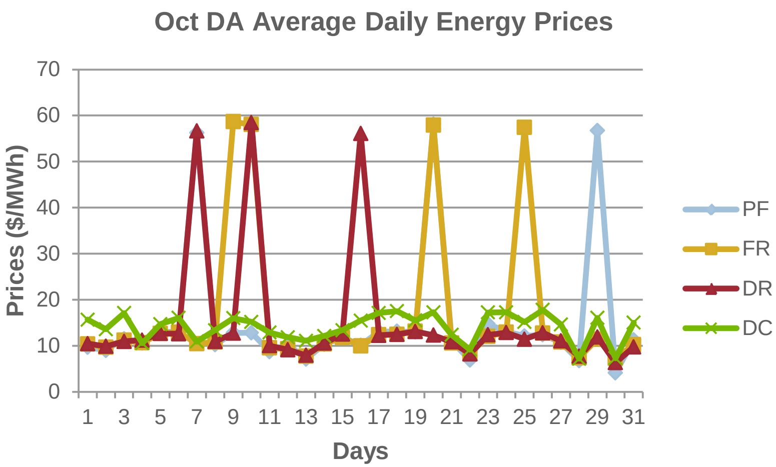


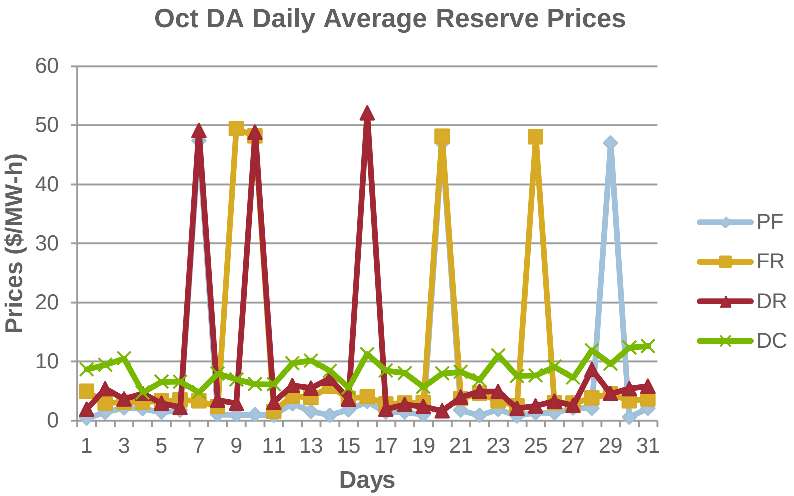
- A demand curve for operating reserves
  - Gives higher prices for energy and reserves in most hours, fewer extreme price spikes
  - Stabilizes revenue stream for thermal generators; can alleviate “missing money” problem
  - Better reflects wind power forecast uncertainty in prices

Average Daily Operating Reserves Prices

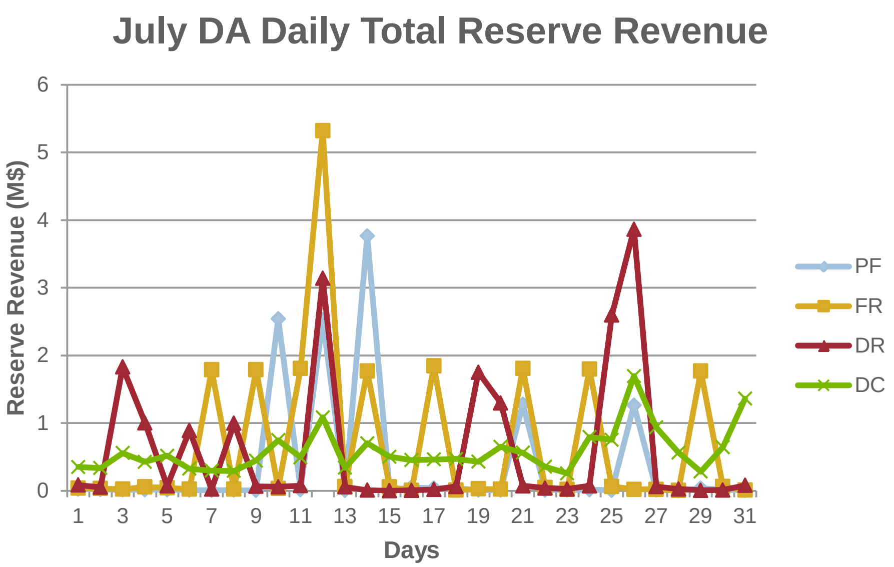


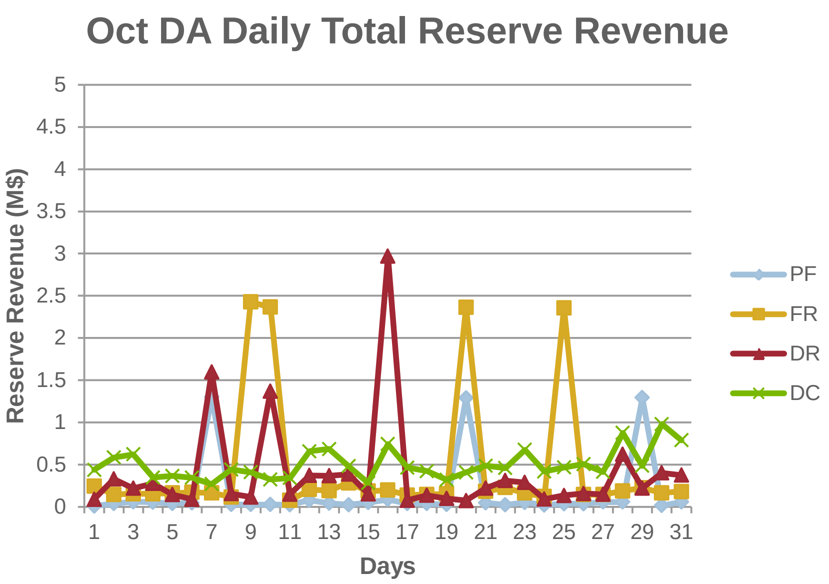






Impact on Operating Reserve Revenue





- A demand curve for operating reserves stabilizes the revenue stream

Overview of Total Operating Cost

- High load period (July)

RT-Cost (M$)	PF	FR	DR	DC
Total	198.74	212.91	209.02	215.07
Fuel	189.39	202.08	199.58	207.03
Startup	9.33	9.67	8.93	8.04
Curtailment	0.02	1.16	0.51	NA

- Low load period (October)

RT-Cost (M$)	PF	FR	DR	DC
Total	96.46	117.68	115.71	110.67
Fuel	89.63	106.31	107.93	102.30
Startup	6.83	8.57	7.58	8.37
Curtailment	0.00	2.80	0.20	NA

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Conclusion and Future Work

- **A demand curve for operating reserves**
  - Provides prices that better *reflect the marginal reliability* of the system as a function of the reserve level, accounting for multiple uncertainties (load, outages, wind).
  - Contributes towards *more efficient market operations* through improved price signals for short-term operation and maintenance, and long-term system expansion.
  - Is a solution that *is compatible with current market designs*.
  - Tends to schedule more reserves than price-inelastic reserve requirements in case study.

- **Future work**
  - Introduce transmission network / locational operating reserve demand curves.
  - Reserve provision from wind power and demand.
  - Supply curves from ancillary service providers.

References and Acknowledgements

- References for more information

  - Zhou Z., Botterud A., “Price Responsive Demand for Operating Reserves and Energy in Electricity Markets with Wind Power,” IEEE Power & Energy Society Annual Meeting, Vancouver, Canada, July 2013.
  - Zhou Z., Botterud A., Wang J., Bessa R.J., Keko H., Sumaili J., Miranda V., “Application of Probabilistic Wind Power Forecasting in Electricity Markets,” *Wind Energy*, Vol. 16, No. 3, pp.321-338, 2013.
  - Bessa R.J., Miranda V., Botterud A., Zhou Z., Wang J., “Time-Adaptive Quantile-Copula for Wind Power Probabilistic Forecasting,” *Renewable Energy*, Vol. 40, No. 1, pp. 29-39, 2012.

- Acknowledgements

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Project website: http://www.dis.anl.gov/projects/windpowerforecasting.html

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