FORCES
FOUNDATIONS OF RESILIENT
CYBER-PHYSICAL SYSTEMS

Reducing Price Volatility via Stochastic Storage Control in Power Networks

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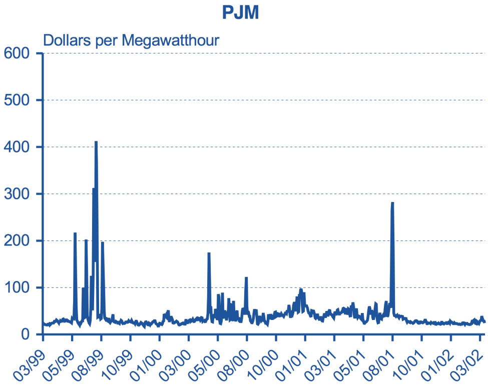
Variation in wholesale electricity prices

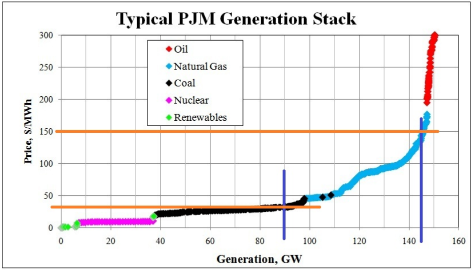
Average annual volatility of commodity prices [DOE, 2002]

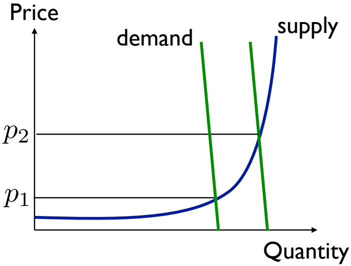
- natural gas & petroleum: 48.5%, metals: 21.8%, agriculture: 49.1%, meat: 42.6%
- **electricity: 359.8%**



Reason I for high price volatility

- Steep rise in supply function
- Inelastic demand





- **Unexpected fluctuation in net demand** changes price a lot
- Texas: wind generation & price volatility

[Woo, Horowitz, Moore, Pacheco, 2011]

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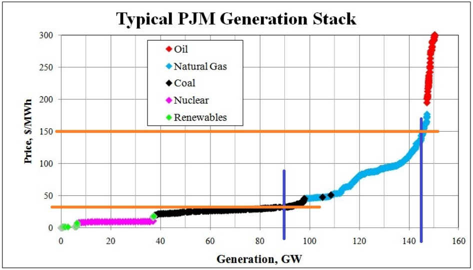

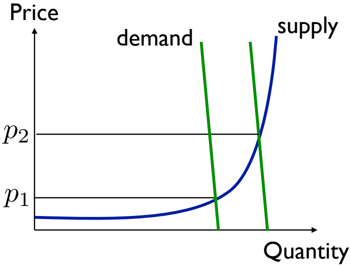

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Reason II for high price volatility

- Locational marginal pricing:
  value of energy at specific location and time it is delivered
- **Transmission congestion**:
  preventing the next-cheap MW of energy from reaching all buses
  (price jumps occur as soon as a line is congested)
- NYISO: price volatility & congestion [Hadsell, Shawky, 2006]
- Will give an example later!

Disadvantages of high price volatility

- **Obstacle to real-time pricing**:
  inefficient markets [Borenstein, 2005]
- **Difficult to predict supplier's revenue**:
  decelerating investments and innovations in generation technology [Gross, Blyth, Heptonstall, 2010]
- **Utility's revenue risks**:
  unstable profits, bankruptcy [Oum, Oren, Deng, 2006]

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Our approach: stochastic storage control

- Reduce intraday *price volatility* while minimizing generation costs by shifting energy
  - **across time: energy storage**
  - **across space: transmission network**

- Optimal decision making under uncertainty in *net demand* (= demand − renewables)
  - **distributional information of net demand**

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Advantages and findings

- Optimally shifts energy over **time (via storage)** and **space (via transmission lines)** by fully utilizing the **distributional information of uncertain net demand**

- **Does not interfere with currently used economic dispatch** rule in real-time markets:
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Real-time economic dispatch

- w_i: *stochastic* net demand at bus (node) i
- u_i: power charged to storage at bus i

Real-time economic dispatch given storage output u:

$$\min_{P,\theta} \quad \sum_{i=1}^{n} C_i(P_i) \quad \text{cost minimization}$$

$$\text{s.t.} \quad P_i - w_i - u_i = \sum_{j=1}^{n} B_{ij}(\theta_i - \theta_j) \quad \text{linearized "DC" power flow}$$

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Locational marginal price (LMP)

KKT condition:

$$\frac{dC_i(P_i)}{dP_i} = \lambda_i \quad \text{(LMP)}$$

$$\sum_{j=1}^{n} B_{ij}[\lambda_i - \lambda_j + \mu_{ij} - \mu_{ji}] = 0 \quad \text{(LMP variation over network)}$$

$$\mu_{ij}[B_{ij}(\theta_i - \theta_j) - L_{ij}] = 0 \quad \text{(complementary slackness)}$$

ex) no network congestion:

$$\mu_{ij} \equiv 0 \quad \text{no line congestion}$$

$$\lambda_1 = \cdots = \lambda_n \quad \text{single price}$$

Function representation of economic dispatch

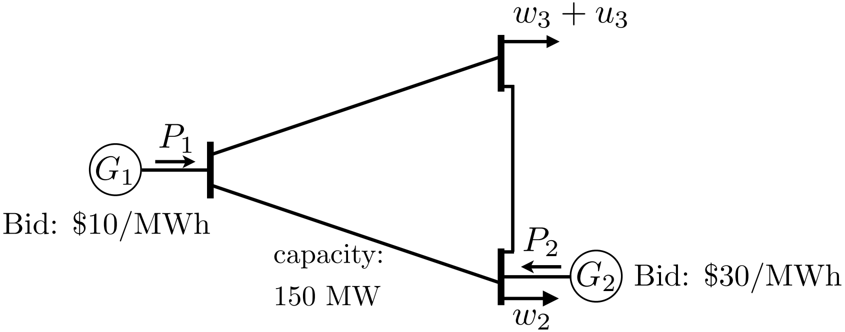
- P_i, λ_i: outcome of economic dispatch given (u, w)
- Define functions $\boldsymbol{P}_i$ and $\boldsymbol{\lambda}_i$ such that

$$\boldsymbol{P}_i(u, w) = P_i$$
$$\boldsymbol{\lambda}_i(u, w) = \lambda_i$$

- Will be used in connecting economic dispatch and stochastic storage control!

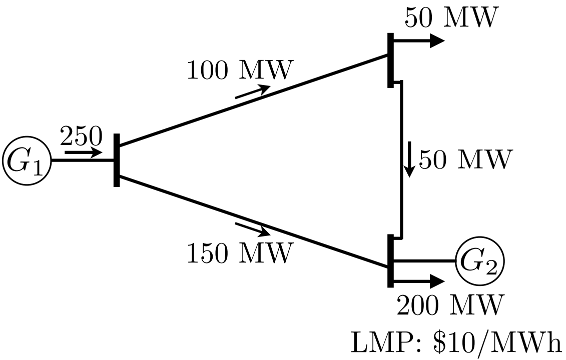
Network effect on price jumps

- A three bus network: parameter and setting



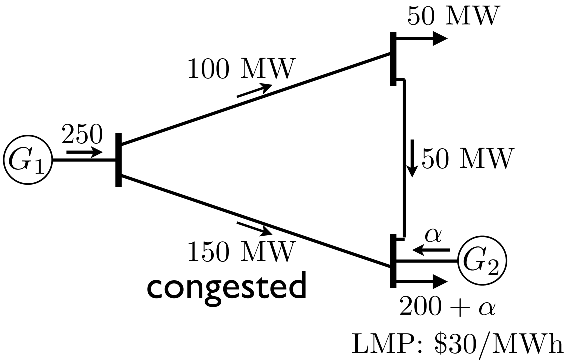
Network effect on price jumps

- Base case: $w_2 = 200,\ w_3 = 50,\ u_3 = 0$



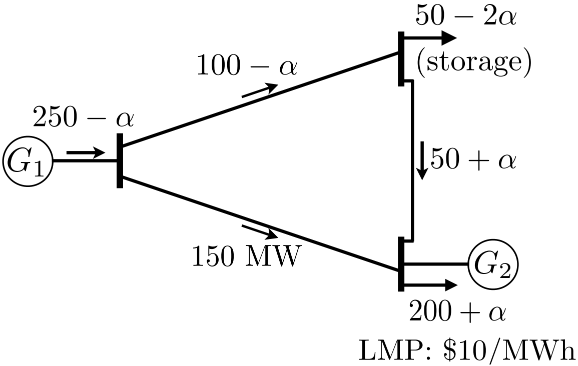
Network effect on price jumps

- **Congestion and price jump**: $w_2 = 200 + \alpha$, $w_3 = 50$, $u_3 = 0$



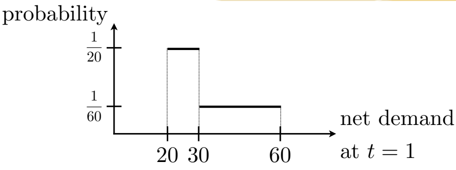
Network effect on price jumps

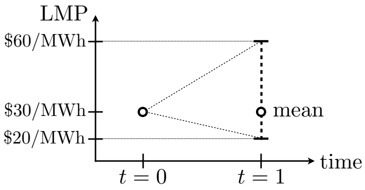
- **Canceling the price jump using storage**



Net demand uncertainty and price volatility

- A two stage problem





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- stochastic optimal control: discharge 5MW
  using the distributional info., can **reduce volatility by** 15%

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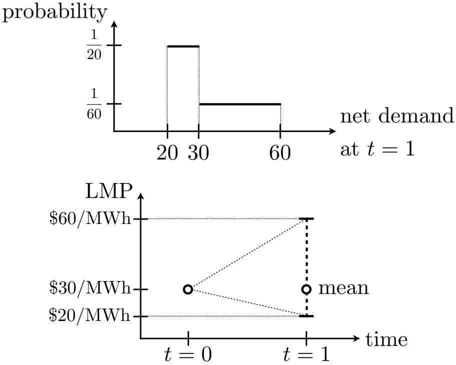

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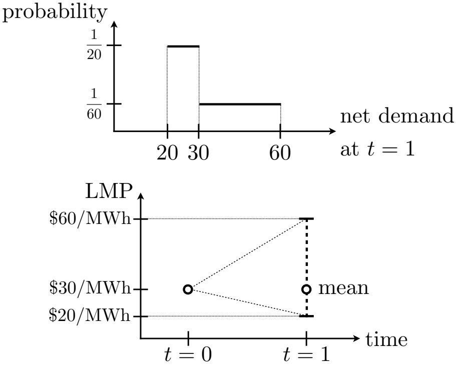

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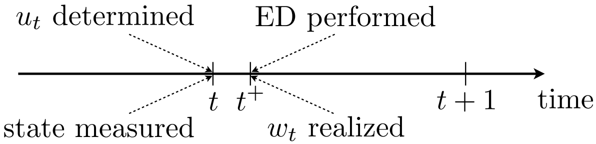
Connecting stochastic storage control and economic dispatch (ED)

- Timeline
  - States (state-of-charge, LMP) are measured
  - Control action u_t for energy storage is determined
  - Net demand w_t is realized
  - Given (u_t, w_t), economic dispatch (ED) is performed



- Storage transparently affects the market parameters through the power flow constraint: **no interference with ED**

Stochastic storage control

$$\min_{\mathbf{u}\in\mathbb{U}} \quad \mathbb{E}\left[\sum_{t=0}^{T-1}\sum_{i\in\mathcal{N}_g} C_{i,t}(\boldsymbol{P}_{i,t}(u_t,w_t))\right] + \sum_{i\in\mathcal{N}_v}\alpha_i \mathrm{Volatility}(\{\boldsymbol{\lambda}_{i,t}(u_t,w_t)\}_{t=0}^{T-1})$$

$$\text{s.t.} \quad x_{i,t+1} = \eta_i x_{i,t} + u_{i,t}, \quad i\in\mathcal{N}_s \quad \text{storage dynamics}$$

$$u_{i,t}\in\mathcal{U}_i(x_{i,t}), \quad i\in\mathcal{N}_s, \quad \text{storage ramping constraint}$$

where

$$\mathrm{Volatility}(q) := \mathbb{E}\left[\sum_{t=1}^{T-1} v(q_t - q_{t-1})\right] \quad \text{expected } v\text{-variation}$$

$$\mathcal{U}_i(\boldsymbol{x}) := [\max\{\underline{x}_i - \eta_i\boldsymbol{x}, \underline{u}_i\}, \min\{\overline{x}_i - \eta_i\boldsymbol{x}, \overline{u}_i\}]$$

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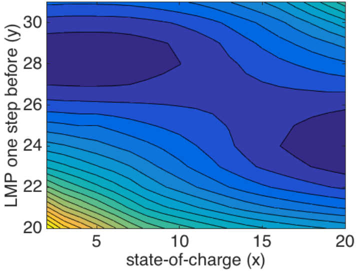
$$

Dynamic programming over a lifted space

- New state variable: LMP at $t-1$

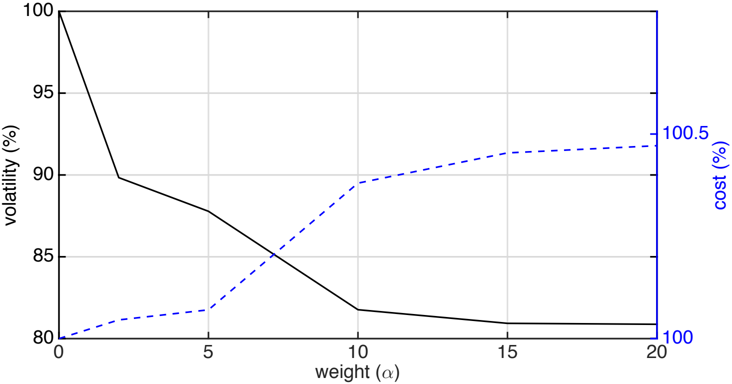
$$y_t := [\boldsymbol{\lambda}_{t-1}(u_{t-1}, w_{t-1})]_{\mathcal{N}_v}$$

- Convexity of value function when LMP is convex nondecreasing in storage injection



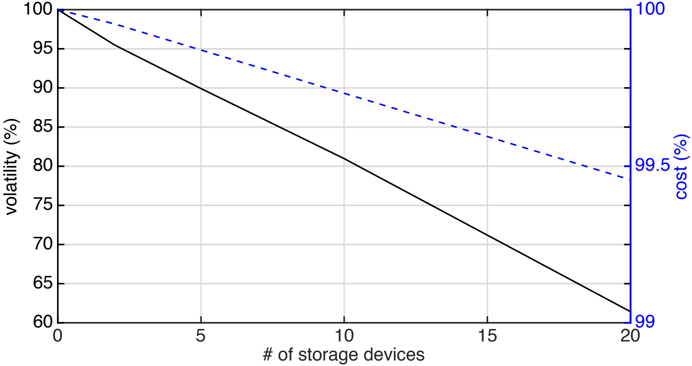
The weight (α) on volatility

- Volatility is reduced by 10%, while the increase in the generation cost is less than 0.1% (when $\alpha = 2$)



The storage capacity

- 10 storage devices: **0.27% cost saving**
- same setting: **19% volatility reduction**



Conclusion and future directions

- Stochastic storage control method to shift energy across time and space
- Optimal decision making using distributional information of net demand
- No modification of currently used economic dispatch rule
- Effectiveness of energy storage on price volatility

Ongoing/future work

- Distributed operation of stochastic storage controllers
- Economic value of reducing price variations
- Risk management potential of storage