Hedging Strategies for Load-Serving Entities in Wholesale Electricity Markets

D.P. Zhou, M.A. Dahleh, and C.J. Tomlin

[datong.zhou, tomlin]@berkeley.edu, dahleh@mit.edu

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Introduction

The "Hockey Stick"

Figure: Supply and Demand in Electricity Markets

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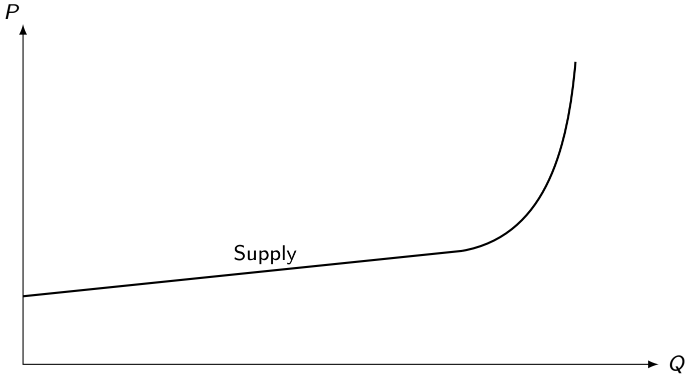

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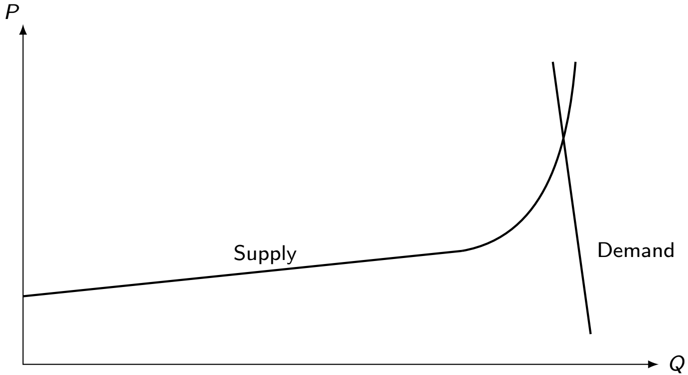

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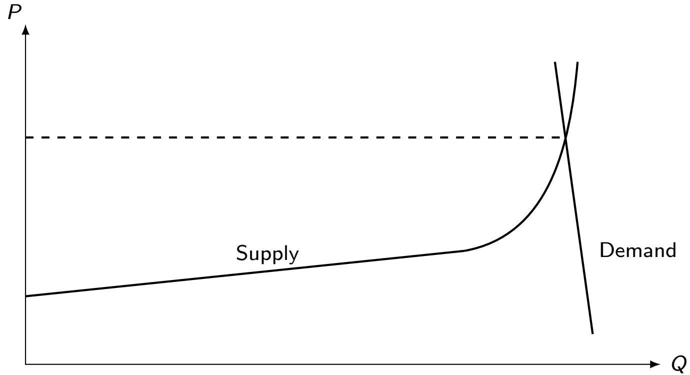

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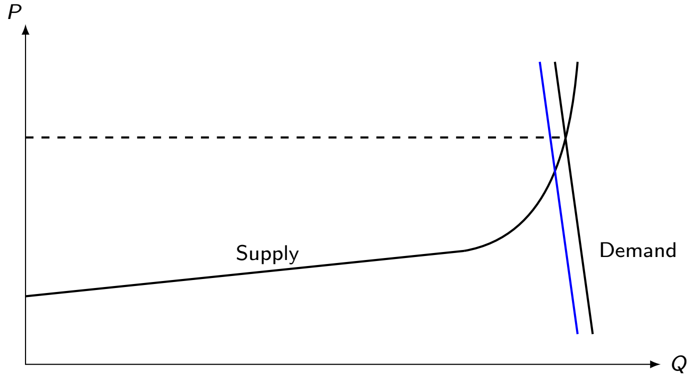

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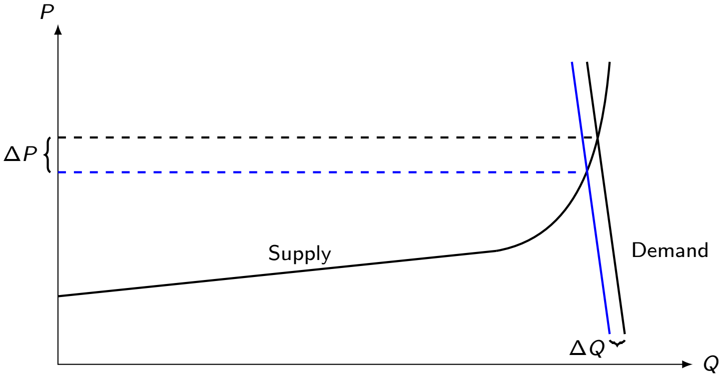

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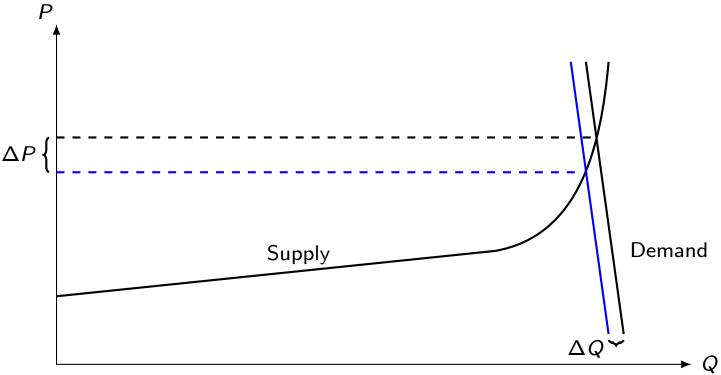

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Restructuring of Electricity Markets

- 1996: FERC Orders 888 and 889 to promote competition and market efficiency

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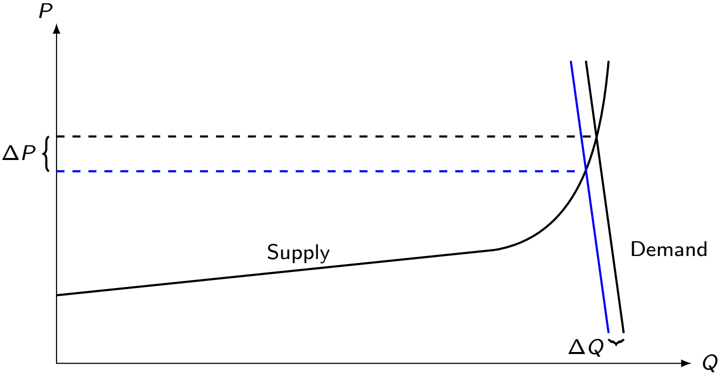

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- 1996: FERC Orders 888 and 889 to promote competition and market efficiency
- Retention of quasi-fixed electricity tariffs vs. price and quantity risks

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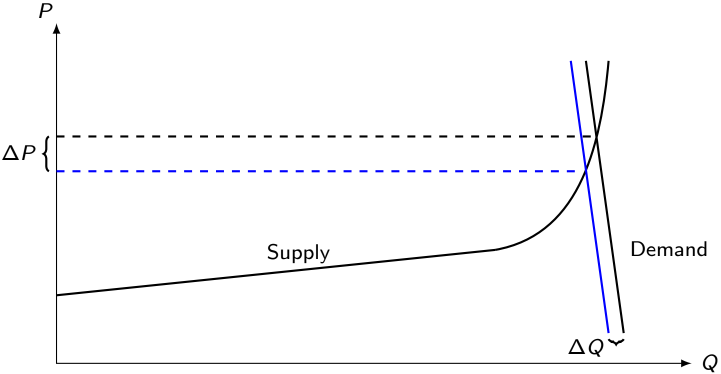

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- 1996: FERC Orders 888 and 889 to promote competition and market efficiency
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- 2000: Wholesale prices of $\approx$ 150 USD/MWh in California

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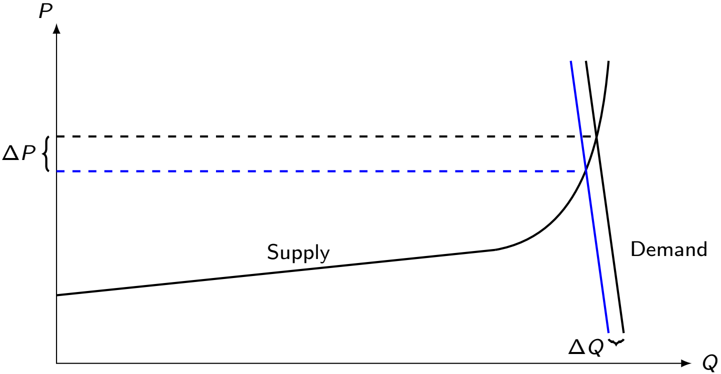

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Restructuring of Electricity Markets

- 1996: FERC Orders 888 and 889 to promote competition and market efficiency
- Retention of quasi-fixed electricity tariffs vs. price and quantity risks
- 2000: Wholesale prices of ≈ 150 USD/MWh in California
- Introduction of Demand Response and contracts between utilities and generators

Hedging Instruments in Wholesale Electricity Markets

Background

- Electric utilities face *price and quantity risks*:
  - Provide electricity to end users instantaneously, at all times, at a fixed tariff
  - Locational Marginal Prices (LMPs) vary due to grid congestion, operational constraints, demand fluctuations
  - Energy storage prohibitively costly
- Generating companies face similar issues

Open Questions

- Contracts between generators and utility to alleviate risk?
- Hedging Instruments
  - One-to-one contracts/options between generators and the utility
  - Demand Response to relay risk from utility to end-users
- Comparison of utility profit under different options in the face of uncertainty?

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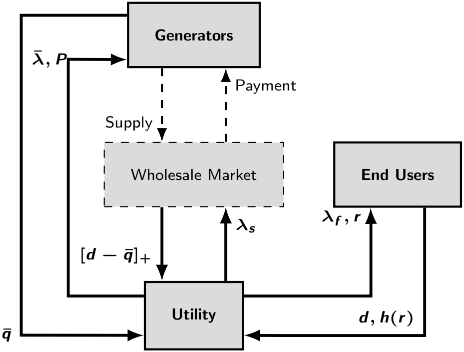

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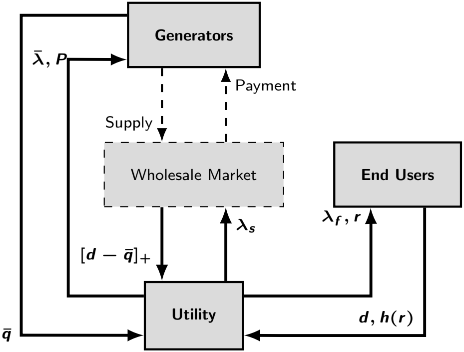

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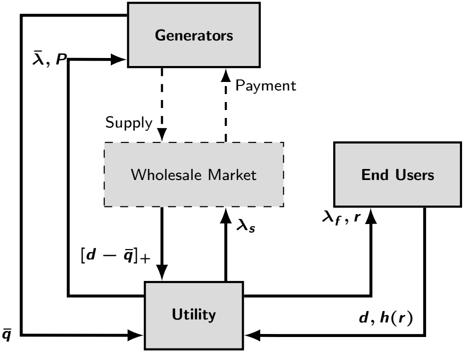

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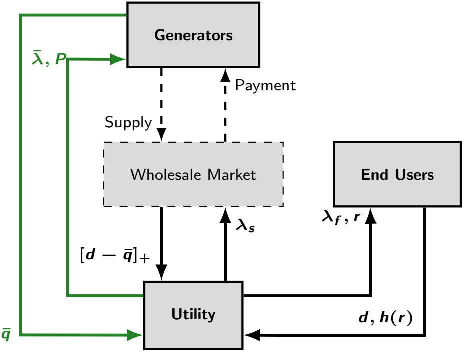

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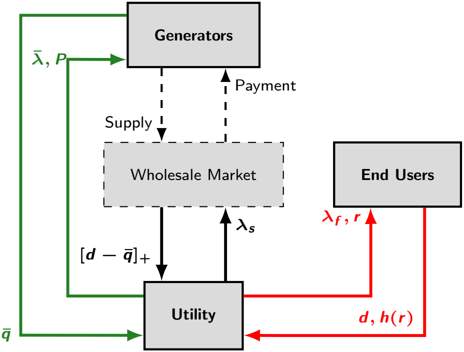

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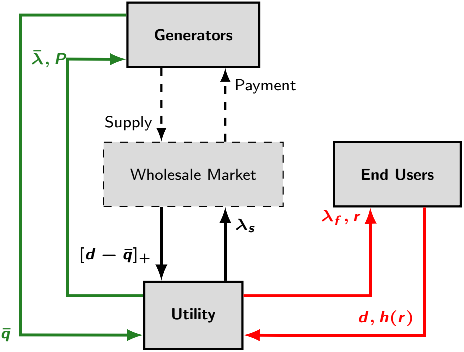

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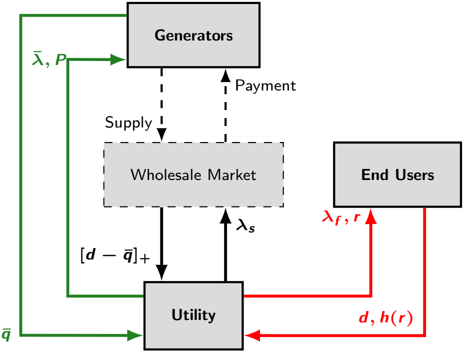
Generator ↔ Utility



Utility ↔ Users

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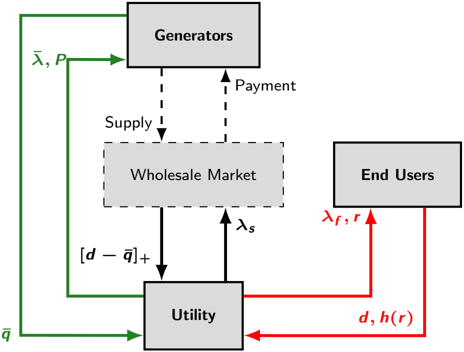
Generator $\leftrightarrow$ Utility

- Forward Contract: Deliver $\bar{q} \in \mathbb{R}_+$ units at price $\bar{\lambda}_F \in \mathbb{R}_+$ at some point in the future



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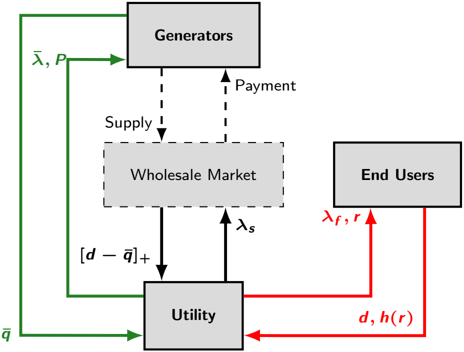

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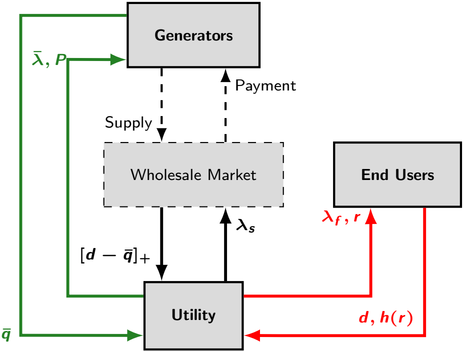

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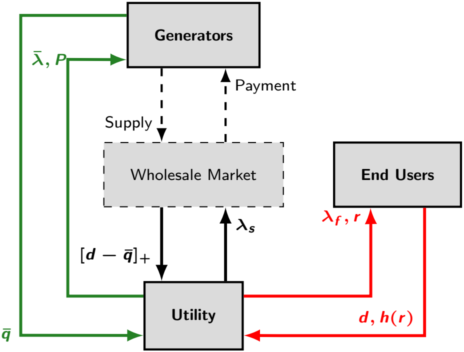
$$\Pi_C = \lambda_f d - \lambda_s \left[d - \bar{q}\right]_+ - P\bar{q} - \min(\bar{\lambda}_C, \lambda_s) \cdot \min(d, \bar{q})$$



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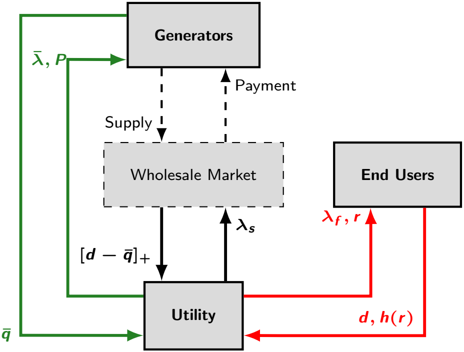
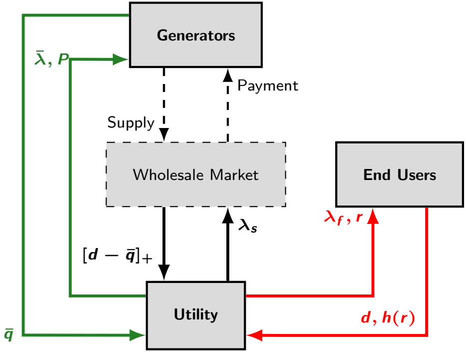


Utility $\leftrightarrow$ Users

- Demand Response: Give incentive $r \in \mathbb{R}_+$ to user. User *reduces* consumption by $h(r) \in \mathbb{R}_+$

$$\Pi_{DR} = (\lambda_f - \lambda_s) d(r) - r$$

Optimal Contracts



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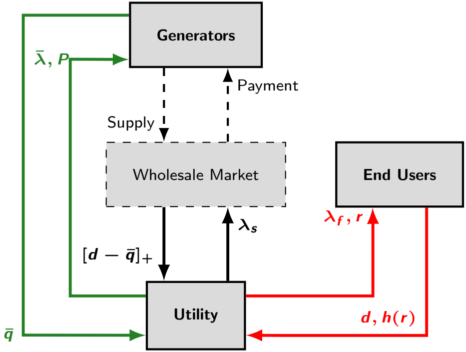


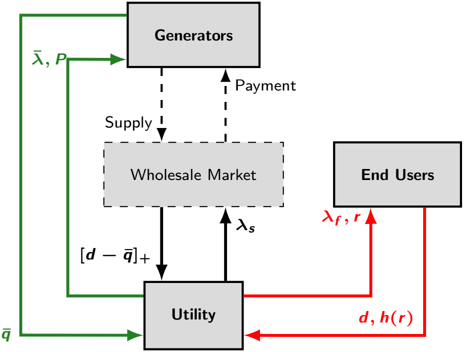
- Demand d, CDF F, PDF f
- Wholesale price λ_s, CDF G
- Fixed residential tariff λ_f
- Utility's profit Π

Optimal Contracts

Optimal Forward Contract

$$\bar{q}^* = F^{-1}\left(1 - \frac{\bar{\lambda}_F}{\mathbb{E}[\lambda_s]}\right)$$

$$\mathbb{E}[\Pi_F^*] = \lambda_f \mathbb{E}[d] - \mathbb{E}[\lambda_s] \int_{F^{-1}\left(1-\frac{\bar{\lambda}_F}{\mathbb{E}[\lambda_s]}\right)}^{\infty} x f(x)\, dx.$$



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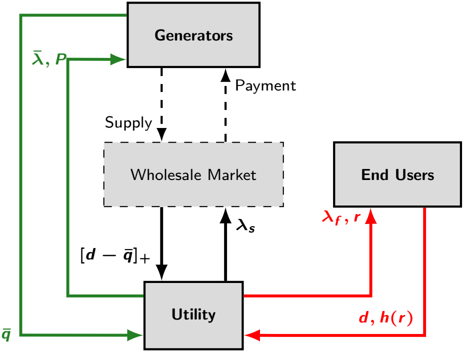

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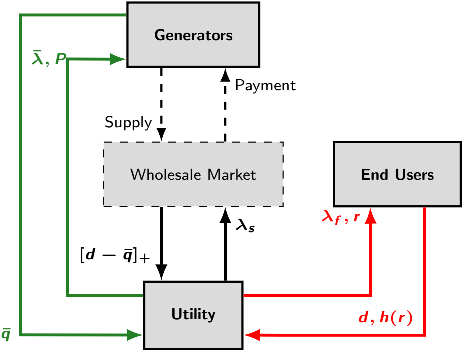
Optimal Demand Response Contract

$$r^* = \begin{cases} \frac{1}{\alpha} F^{-1}\left(1 - \frac{1}{\alpha\cdot(\mathbb{E}[\lambda_s]-\lambda_f)}\right), & \text{if } \frac{1}{\alpha} < \mathbb{E}[\lambda_s] - \lambda_f \\ 0, & \text{otherwise} \end{cases}$$

$$\mathbb{E}\Pi_{\mathrm{DR}}^* = \begin{cases} (\lambda_f - \mathbb{E}[\lambda_s]) \int_{\alpha r^*}^{\infty} xf(x)dx, & \text{if } \frac{1}{\alpha} < \mathbb{E}[\lambda_s] - \lambda_f \\ (\lambda_f - \mathbb{E}[\lambda_s])\, \mathbb{E}[d], & \text{otherwise} \end{cases}$$



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Influence of Uncertainty

Influence of Distribution Tail

- Conditional Value-at-Risk (CVaR) given confidence level $\alpha \in (0,1)$ and CDF $F(\cdot)$ of random variable X:

$$\text{CVaR}_\alpha(X) = \mathbb{E}[X \mid X \geq F^{-1}(\alpha)]$$

- Expected loss in the worst $(1-\alpha)\cdot 100\%$ of cases / expectation of $(1-\alpha)$ probability tail of X

$$\mathbb{E}[\Pi_F^*] = \lambda_f \mathbb{E}[d] - \bar{\lambda}_F \cdot \mathrm{CVaR}_{\alpha_F}(d)$$

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$$\mathbb{E}[\Pi_{\mathrm{DR}}^*] = -\frac{1}{\alpha} \cdot \mathrm{CVaR}_{\alpha_{\mathrm{DR}}}(d)$$

- Expected profit decreases linearly in CVaR.

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Influence of Uncertainty (cont'd.)

Influence of Statistical Dispersion

- Intuition: The more spread out $F(\cdot)$, the lower the expected profit.
- For simplicity: Express optimal profits in terms of standard deviation σ of uniform distribution on $[d_{\min}, d_{\max}]$

$$\mathbb{E}[\Pi_F^*] = \lambda_f \mathbb{E}[d] - \bar{\lambda}_F d_{\min} - \sqrt{3}\mathbb{E}[\lambda_s](1-\alpha_F^2)\sigma$$

$$\mathbb{E}\Pi_C^* = \left(\lambda_f - \bar{\lambda}_C + \int_0^{\bar{\lambda}_C} G(y)dy\right)\mathbb{E}[d] - Pd_{\min}$$

$$-\sqrt{3}\left(\mathbb{E}[\lambda_s] - \bar{\lambda}_C + \int_0^{\bar{\lambda}_C} G(y)dy\right)(1-\alpha_C^2)\sigma$$

$$\mathbb{E}[\Pi_{\mathrm{DR}}^*] = -d_{\min}/\alpha - \sqrt{3}(\mathbb{E}[\lambda_s] - \lambda_f)(1-\alpha_{\mathrm{DR}}^2)\sigma$$

- Expected profit decreases linearly in σ.

Influence of Uncertainty (cont'd.)

Influence of Statistical Dispersion

- Intuition: The more spread out $F(\cdot)$, the lower the expected profit.
- For simplicity: Express optimal profits in terms of standard deviation σ of uniform distribution on $[d_{\min}, d_{\max}]$

$$\mathbb{E}[\Pi_F^*] = \lambda_f \mathbb{E}[d] - \bar{\lambda}_F d_{\min} - \sqrt{3}\mathbb{E}[\lambda_s](1-\alpha_F^2)\sigma$$

$$\mathbb{E}\Pi_C^* = \left(\lambda_f - \bar{\lambda}_C + \int_0^{\bar{\lambda}_C} G(y)dy\right)\mathbb{E}[d] - Pd_{\min}$$

$$-\sqrt{3}\left(\mathbb{E}[\lambda_s] - \bar{\lambda}_C + \int_0^{\bar{\lambda}_C} G(y)dy\right)(1-\alpha_C^2)\sigma$$

$$\mathbb{E}[\Pi_{\mathrm{DR}}^*] = -d_{\min}/\alpha - \sqrt{3}(\mathbb{E}[\lambda_s] - \lambda_f)(1-\alpha_{\mathrm{DR}}^2)\sigma$$

- Expected profit decreases linearly in σ.

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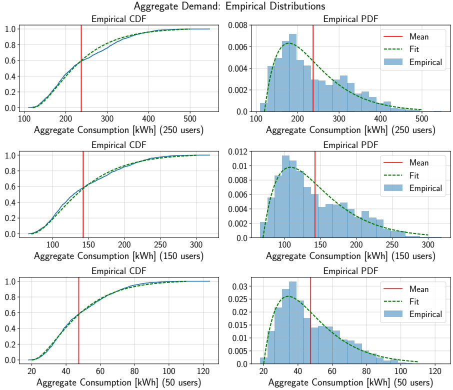
Data Generation for Simulations

Demand Distribution

- Aggregate hourly smart meter data, provided by OhmConnect, Inc.



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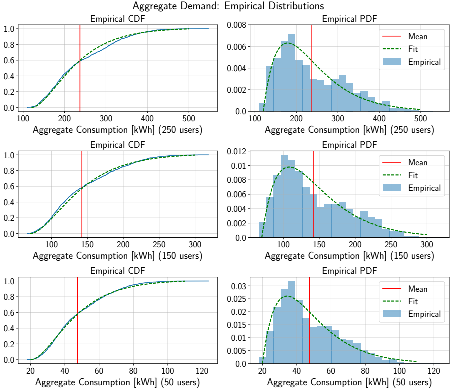
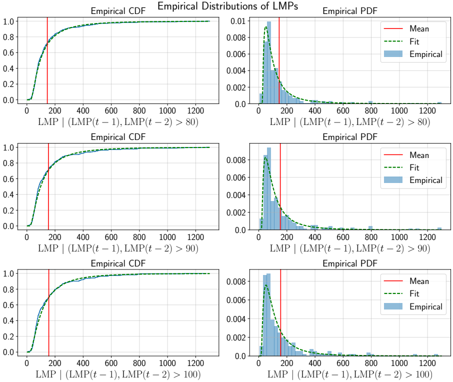


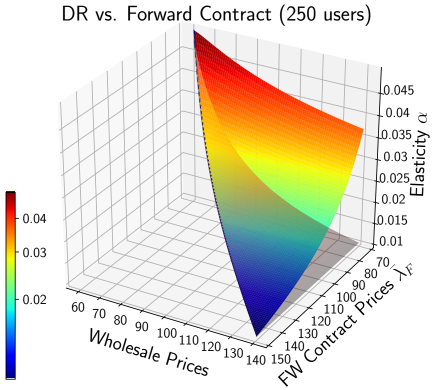
Distribution of LMPs

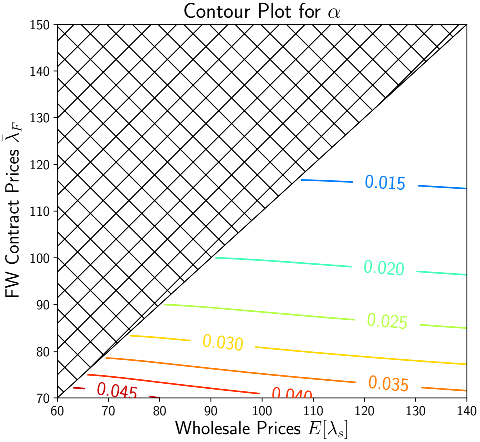
- Scrape 5-minute LMPs from public sources; aggregate to 60-minute values



Pairwise Comparison (I)

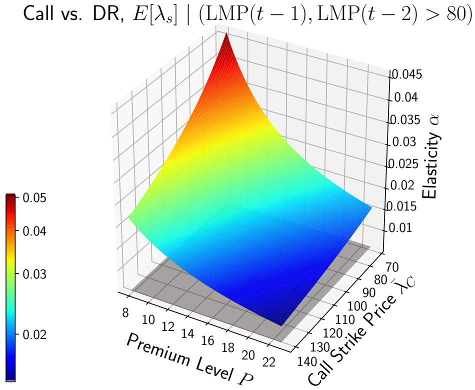
DR vs. Forward Contract

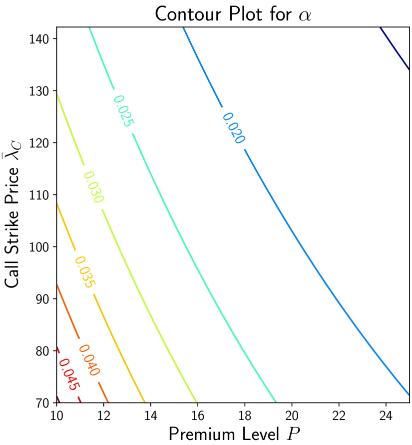




Pairwise Comparison (II)

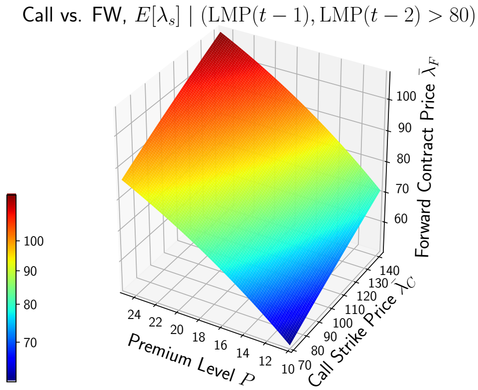
DR vs. Call

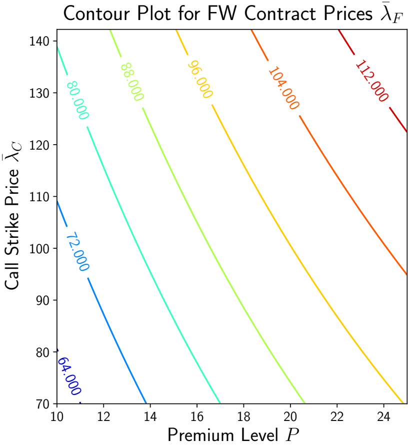




Pairwise Comparison (III)

Forward Contract vs. Call





Conclusion

Summary

- Analyzed hedging instruments for electric utilities to mitigate price and quantity risks
- Profit maximization problem from the perspective of the utility
- Expected profit monotonically decreasing in CVaR / statistical dispersion
- Pairwise comparison of hedging instruments

Future Work

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- Use forecasting methods to model uncertainty in wholesale prices and demand
- Mechanism Design framework between generating companies and utilities

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THANK YOU!
QUESTIONS?