Carnegie Mellon Conference on the Electricity Industry

Impacts of Real-Time Pricing in PJM Territory

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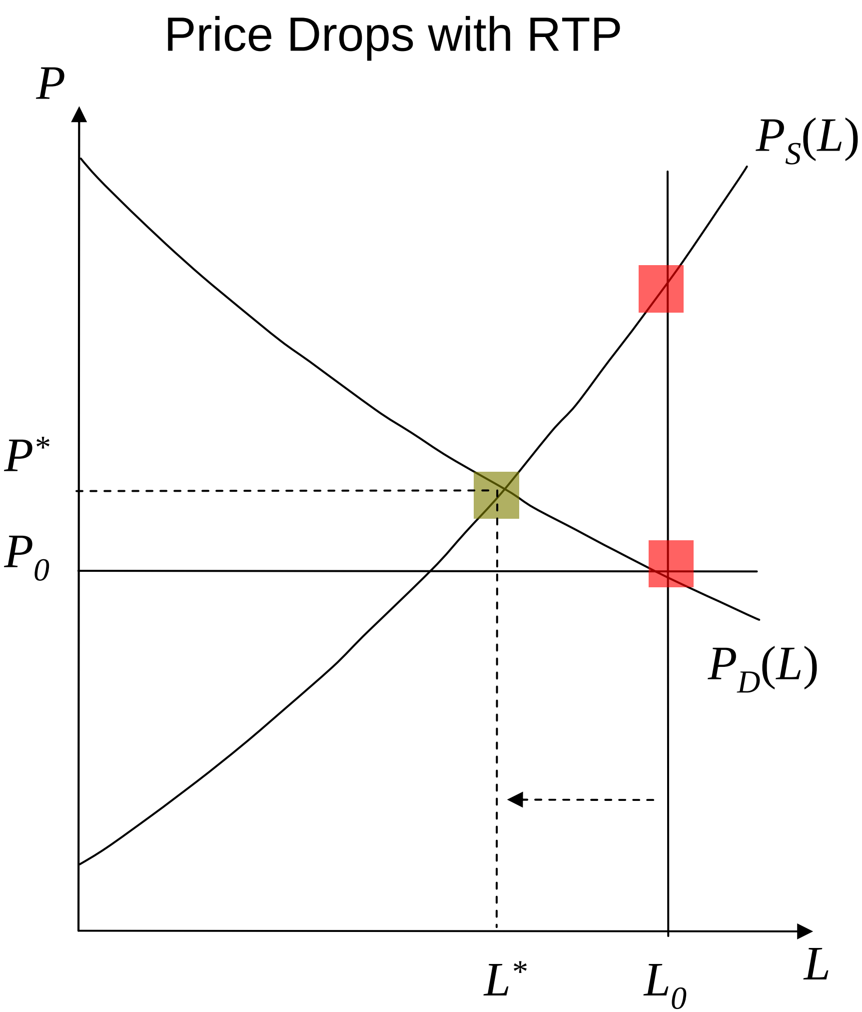
The Peak Load Problem

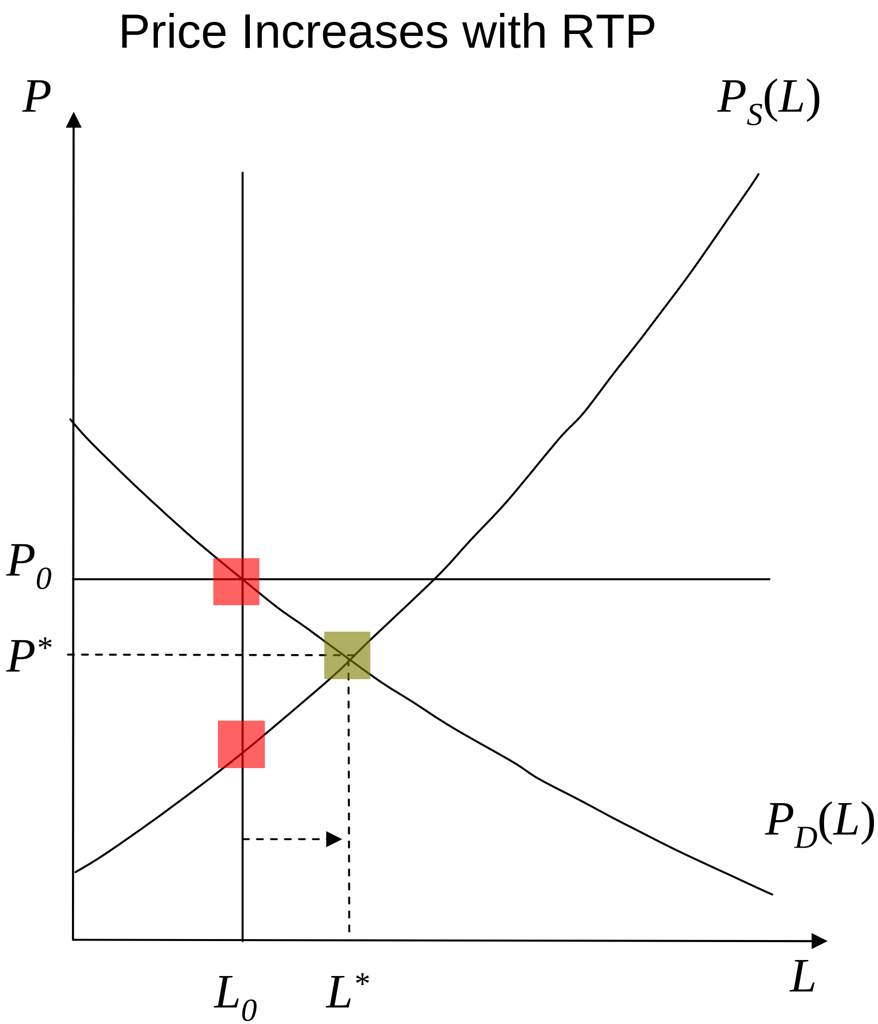
- Peaking capacity is rarely used
  - In PJM in 2006, 15% of generation capacity ran 1.1% or fewer hours, 20% ran 2.3% or fewer hours [1]
  - At $600/kWh overnight capital cost, that 15% is worth $13 billion
- Peak capacity must exceed peak load to prevent blackouts in the next 30 years, but who will pay?
  - What company will invest in these unprofitable peakers?
  - Would consumers opt to pay for these plants via capacity markets if they had the choice?
- Load shifting is an alternative to capacity investments
  - 0.12% of all MWh would have to be shifted away from peak hours to reduce peak load by 15% [1]
  - If the annualized cost of a peaker is $60/kW-year, then an integrated system planner would pay up to $1,600 for each MWh curtailed to flatten peak load

Real-Time Pricing (RTP)

- Under RTP end users' retail rates would change hourly with wholesale prices
- Peak load hours have high prices
  - Some consumers will shift usage away from expensive hours, relieving peak load problems
  - High prices during system emergencies will signal end users to curtail
- Roughly 5% of end user load pays a rate connected with wholesale prices, nearly all of it commercial or industrial [2,3]
- PJM Data
  - Year 2006 market clearing data [1]

Electricity Market Model





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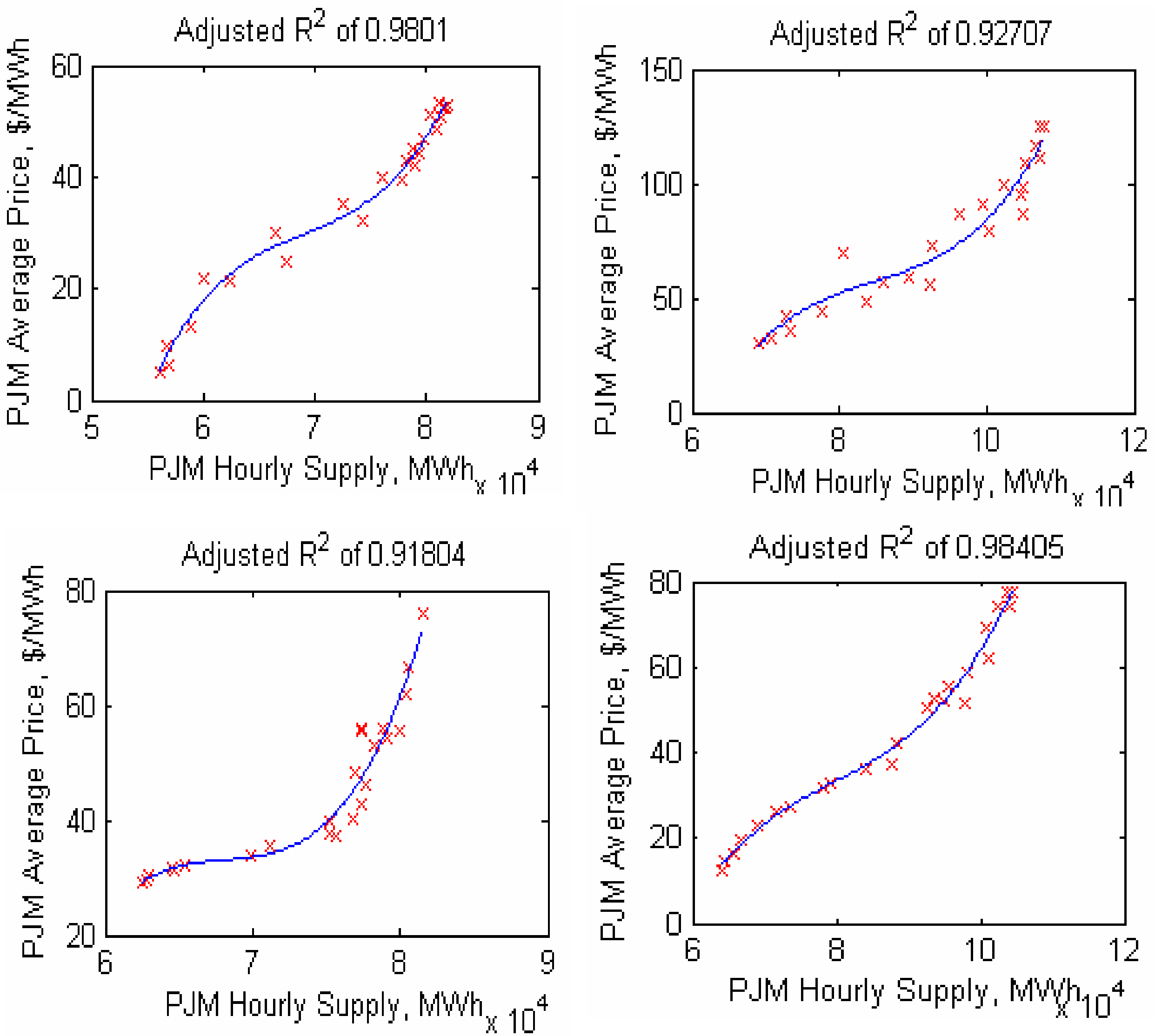
Daily Supply Curves



- Price and load have strong relationship on any given day
- 3rd degree polynomials
- Adjusted R^2 stats:
  - Mean 0.913
  - Median 0.943
  - Range 0.403-0.996

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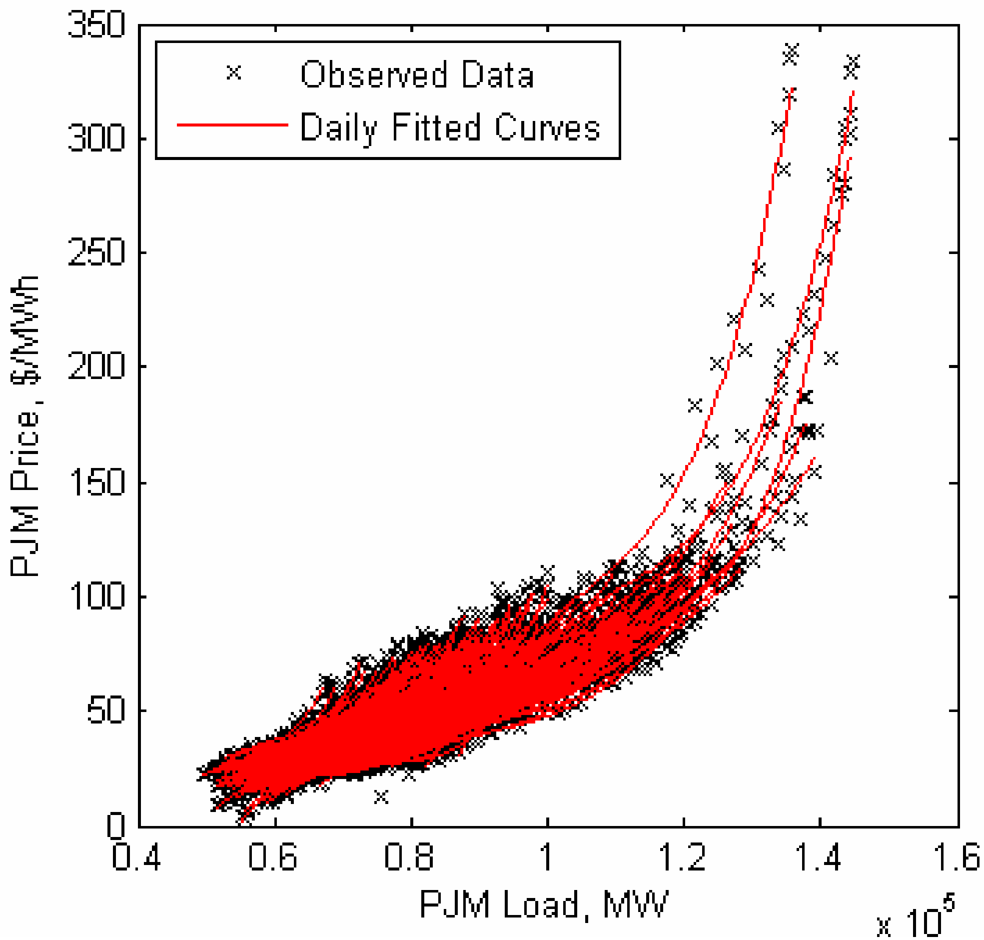
Overall Supply Model with Dummy Variables

$$P_S(L) = \sum_{t=1}^{365} \left\{ \delta_3 \cdot a_t \cdot L^3 + \delta_2 \cdot b_t \cdot L^2 + \delta_1 \cdot c_t \cdot L + \delta_0 \cdot d_t \right\}$$

- Daily 3rd degree polynomials can be represented as one equation with dummy variables
- Overall:
  - Adj $R^2 = 0.966$
  - $365 \cdot 4 = 1460$ parameters



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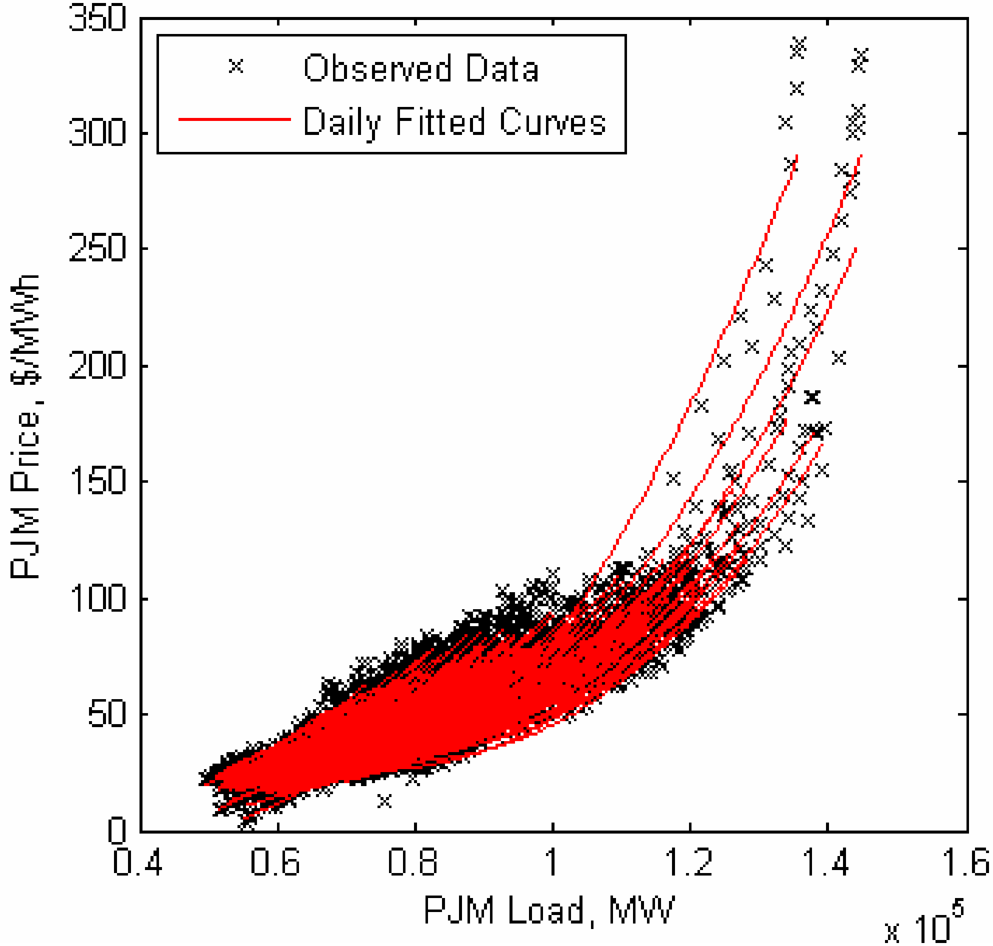
Dropping High-Order Dummy Variables

$$P_S(L) = a \cdot L^3 + b \cdot L^2 + \sum_{t=1}^{n} \{\delta_1 \cdot c_t \cdot L + \delta_0 \cdot d_t\}$$

- Dropping δ_3 and δ_2 halves the parameters and has only a slight effect on explanatory power
- Overall:
  – Adj $R^2 = 0.949$
  – $365 \cdot 2 + 2 = 732$ parameters
- Final Results are nearly unaffected



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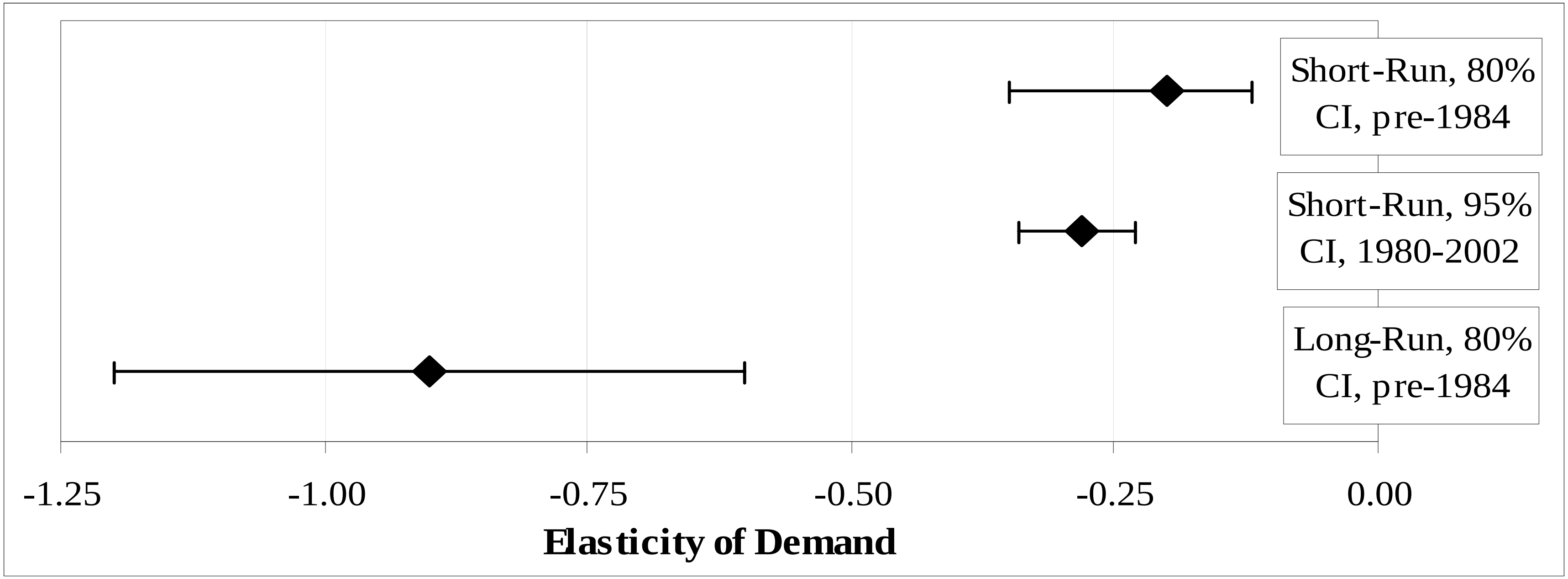
What is the Elasticity of Demand?



[4]

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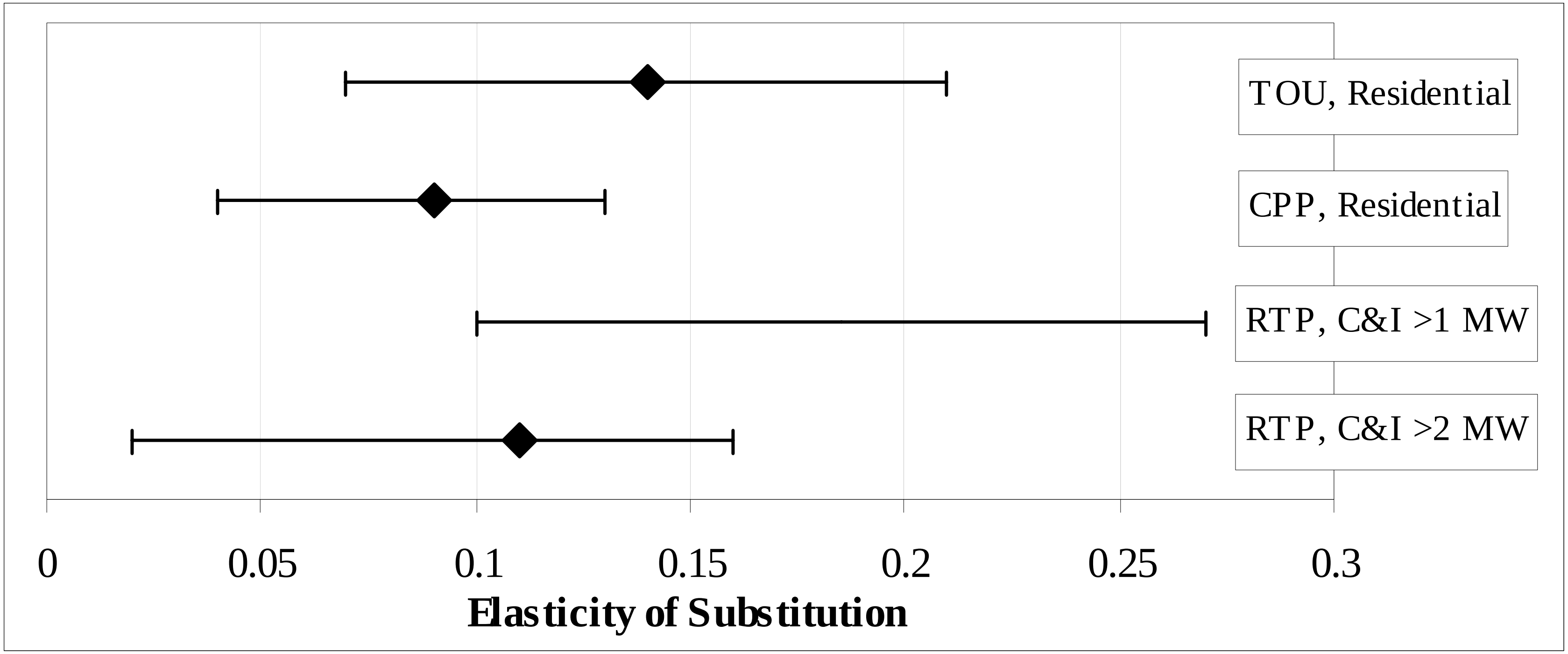
Elasticity of Substitution



[5]

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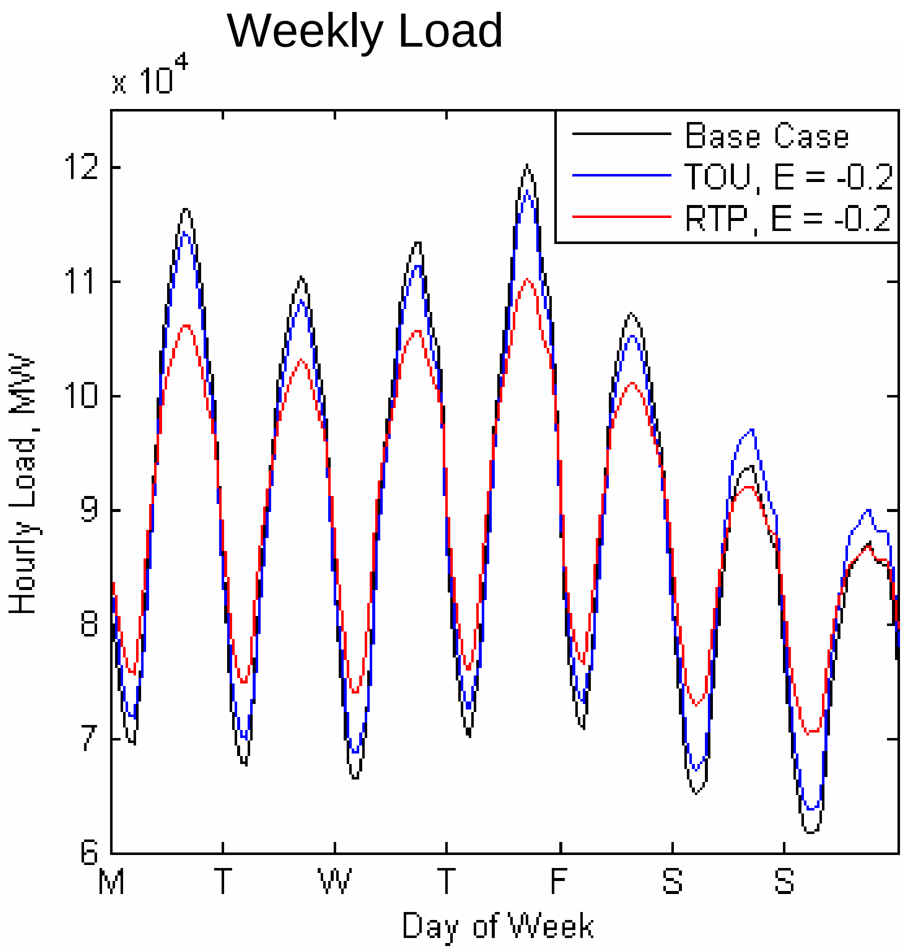
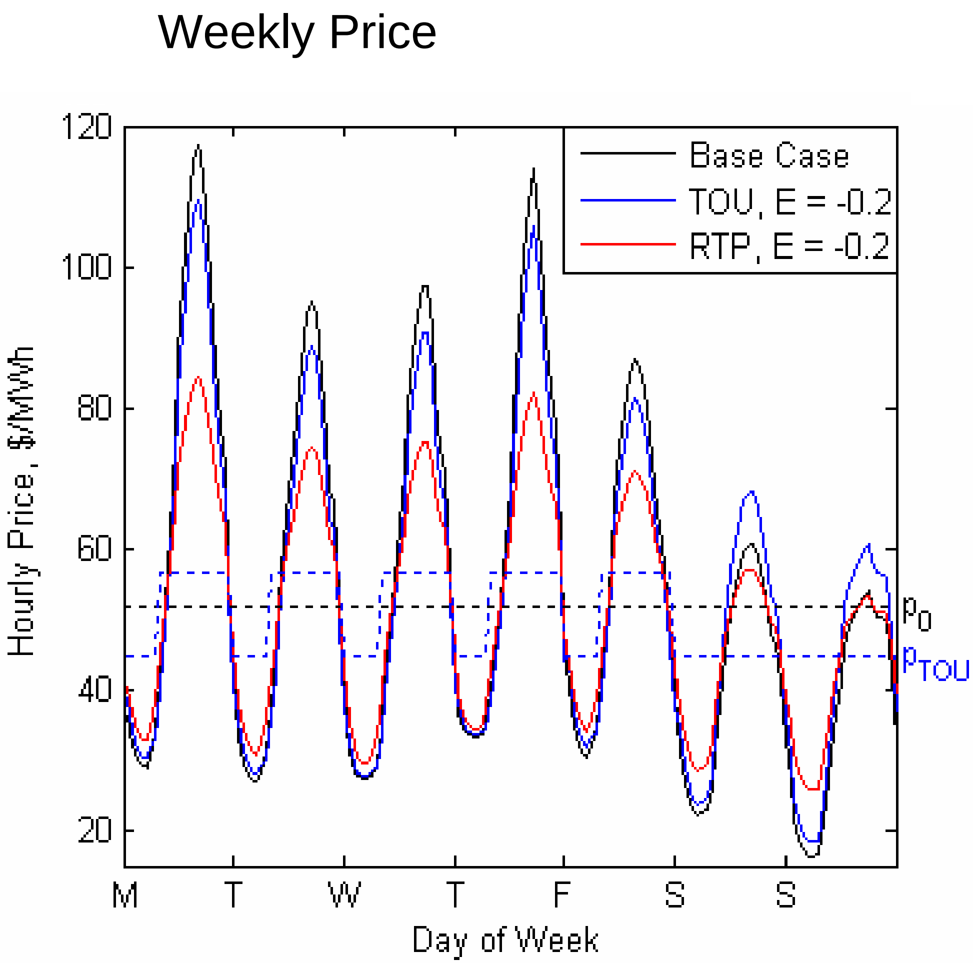
Real Time or TOU Pricing
One High-Load July Week





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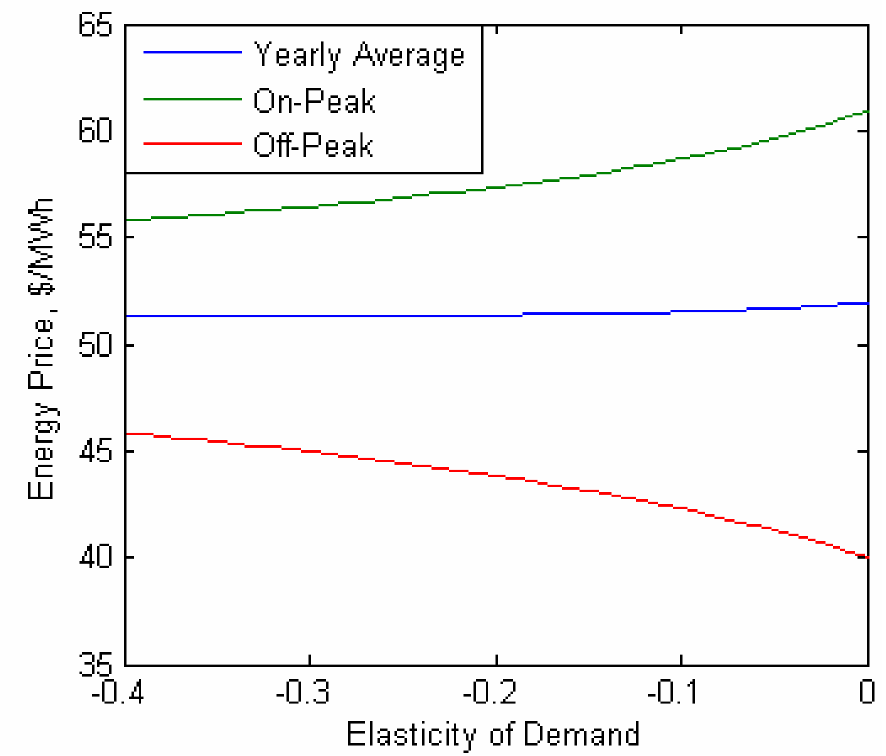
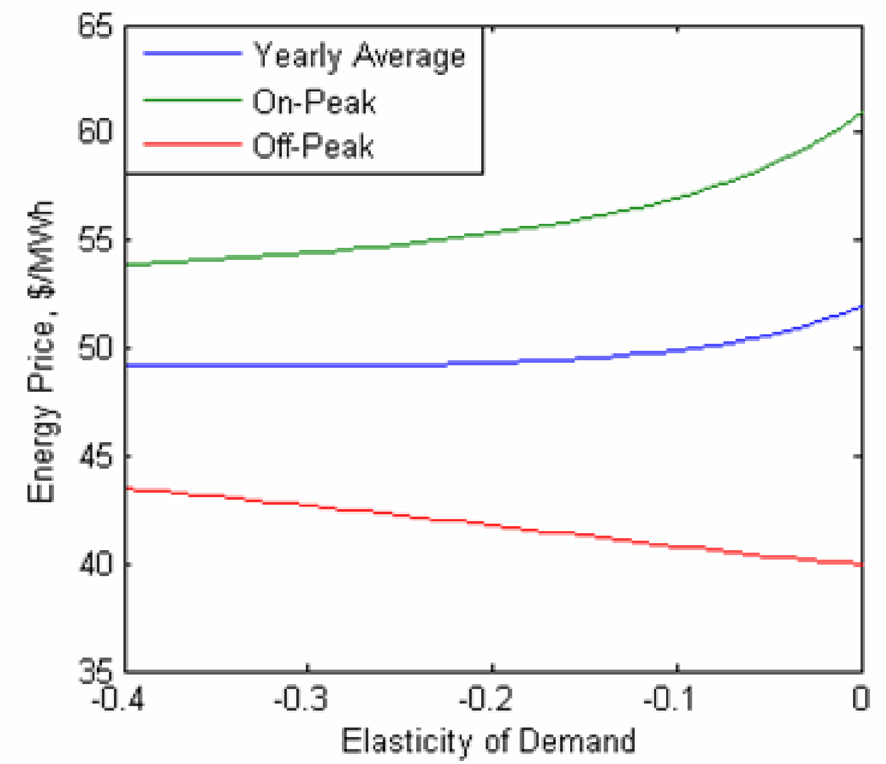
Average Prices

TOU

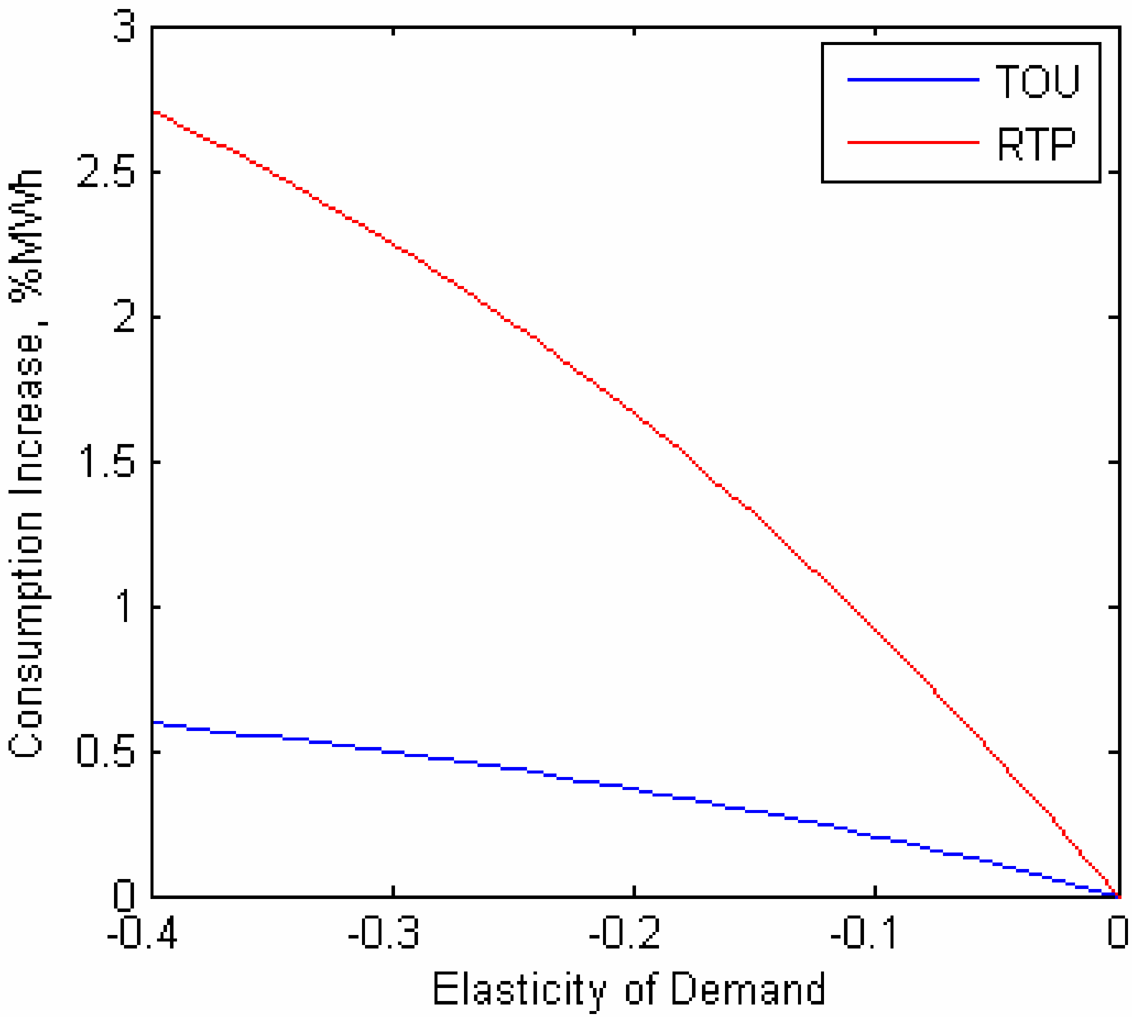


RTP



- Time-dependent retail prices moderate on-peak and off-peak wholesale prices
- If average price is the regulator's only metric of interest, there little difference among flat, TOU, and RTP rates

Consumption Increase



- Customers use more electricity because they see a lower average price
- Environmental concern
  - Greater fossil consumption
  - Shift from gas peakers to baseload coal

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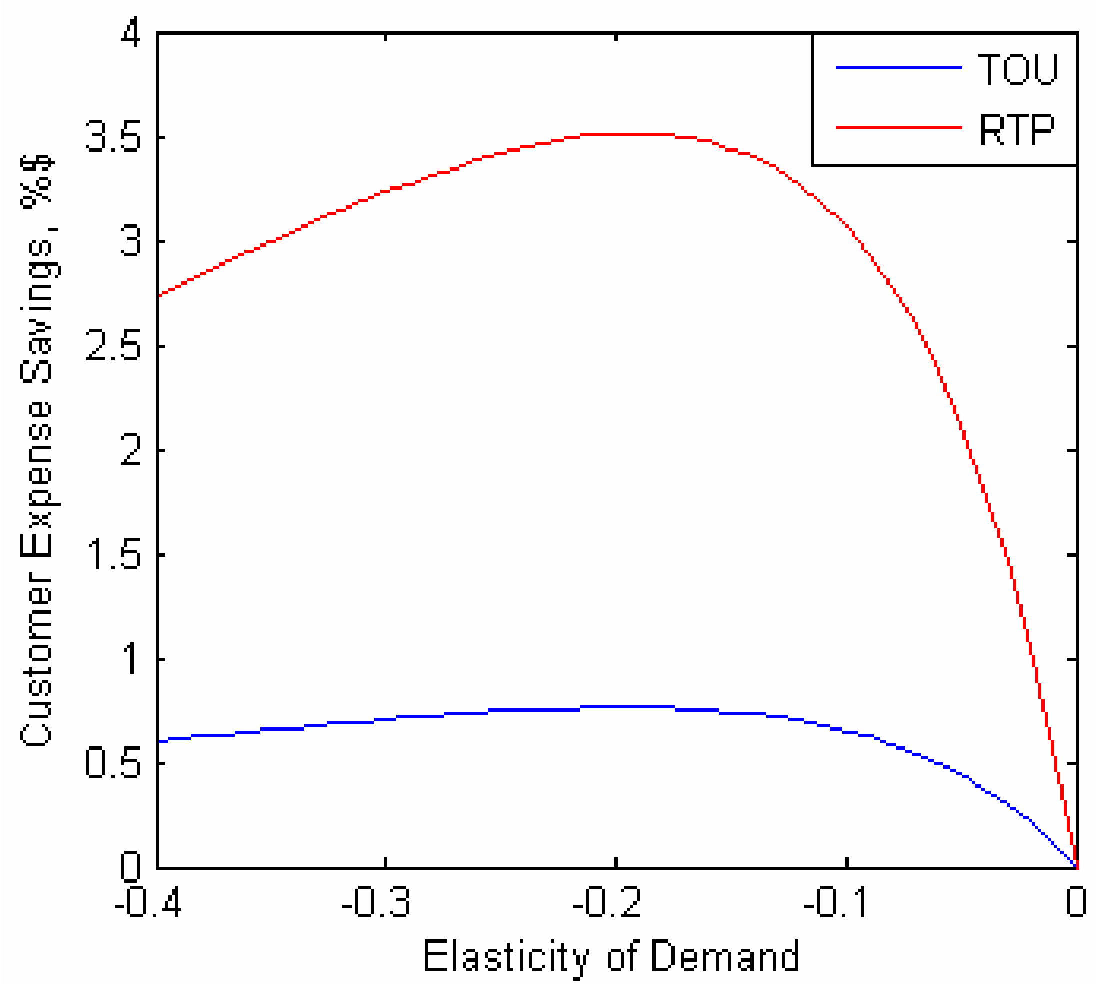
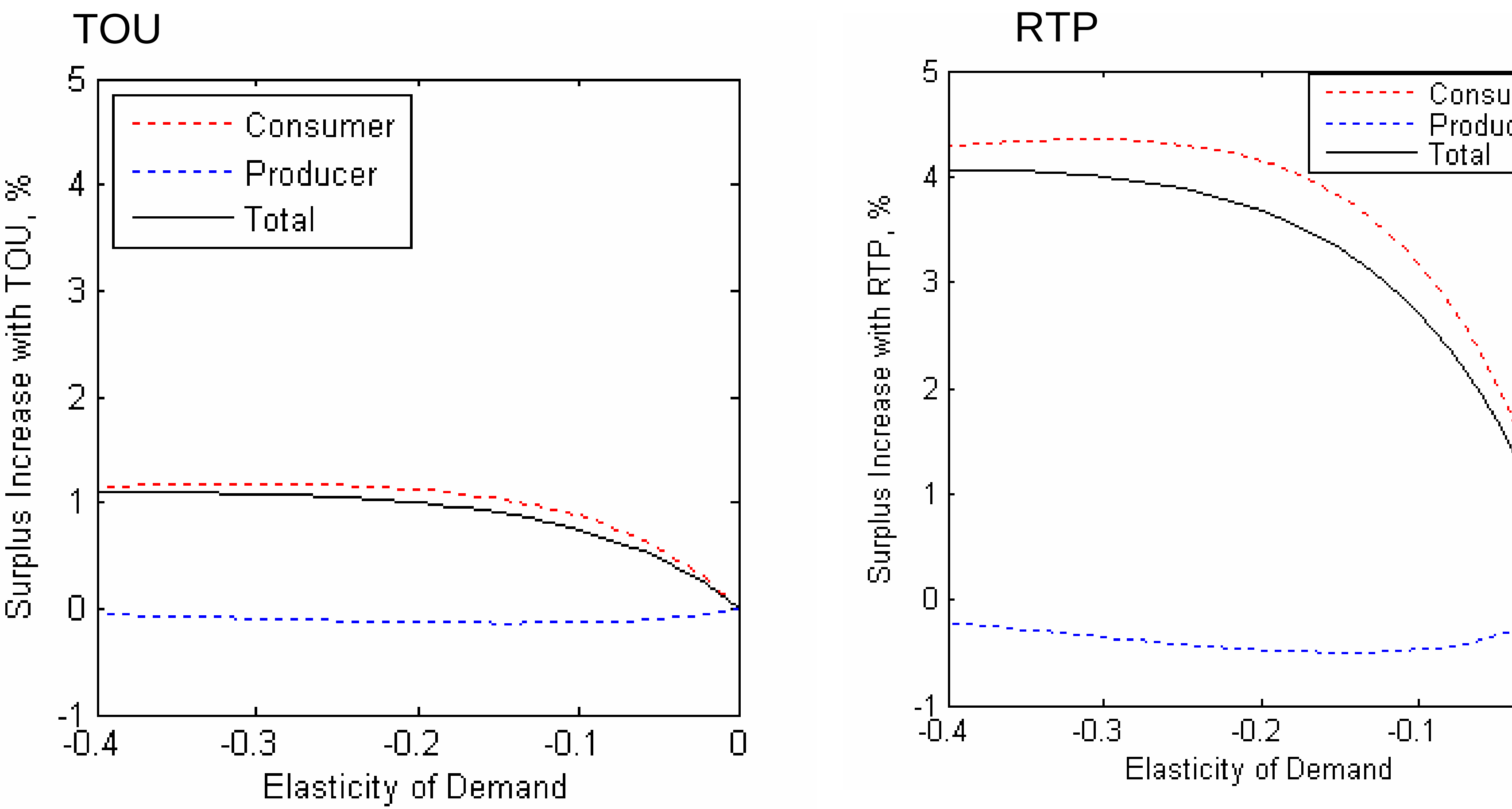
Customer Expense Savings
Generator Revenue Decrease



- The average customer could save more than 3% on her bill with RTP, even though she is also using about 2% more energy

Total Surplus Increase



- Total surplus increases quickly but levels off with greater responsiveness

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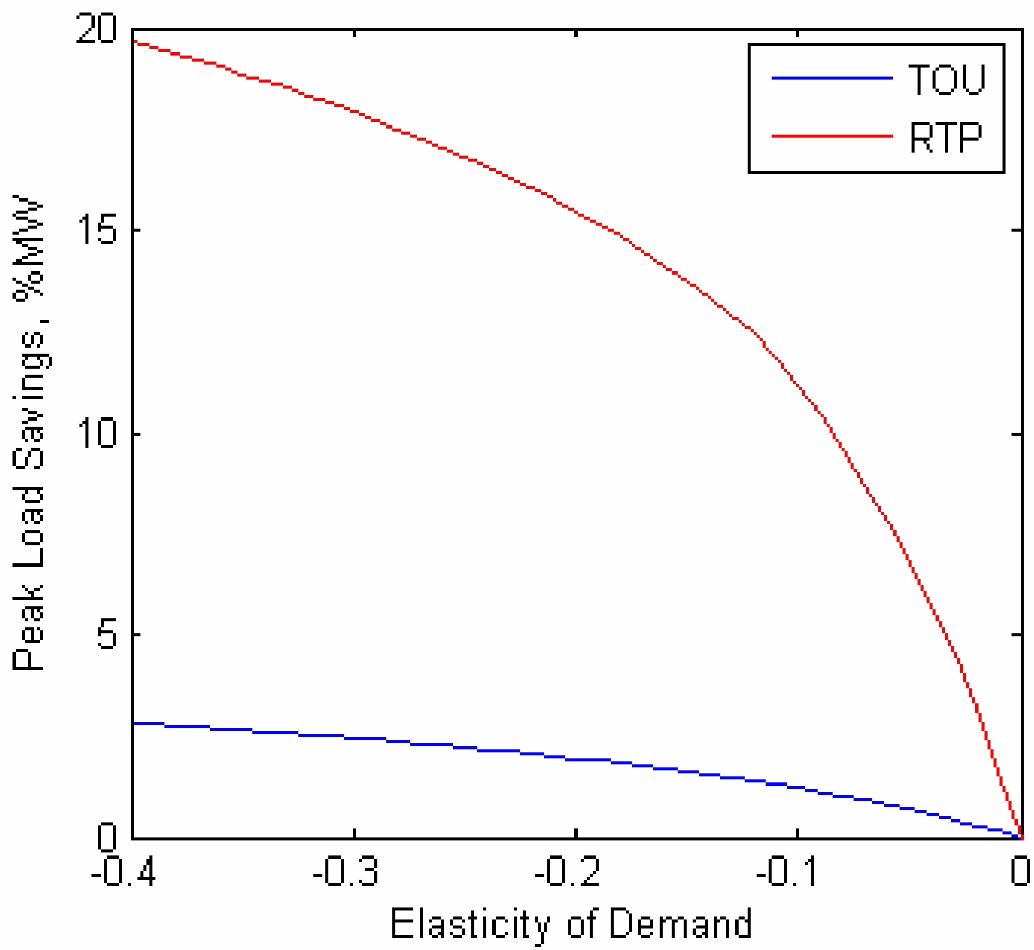
Peak Load Savings



- Peak load shaving is dramatic with even small responsiveness
- If the value of peaking capacity is $600/kW
  - At elasticity -0.1, RTP saves 10.4% of peak load or $9.0 billion in capacity investments
  - At elasticity -0.2, RTP saves 15.1% or about $13 billion

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Policy Implications

- A little responsiveness goes a long way
  - Start with large customers or those who likely to be most responsive
  - Impacts diminish with greater responsiveness
  - At some small customer size, RTP tariffs may not be worth it
- Peak load savings from RTP are large
  - Marginal peak generators will not be scheduled, obviating tens of billions of dollars in capacity investments over PJM
  - RTP will alleviate strain on the grid and associated reliability problems caused by coincident peak load
- RTP can reign in peak loads and peak prices
  - Lowering peak prices benefits all customers whether they respond or not
  - Average prices change only minimally
  - Flat customers no longer subsidize problematic customers with RTP
- TOU rates have about ¼ the benefits of RTP no matter how benefits are measured

Acknowledgements

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2. Assessment of PJM Load Response Programs. PJM Market Monitoring Unit. Report to the Federal Energy Regulatory Commission, Docket No. ER02-1326-006. August 29,2006. Available: http://www.pjm.com/markets/market-monitor/downloads/mmu-reports/dsr-report-2005-august-29-%202006.pdf
3. *2005 Price Responsive Load Survey Results.* Available: http://www.pjm.com/committees/working-groups/dsrwg/downloads/20060615-05-price-responsive-load-survey.pdf
4. King, Chris S, and Sanjoy Chatterjee. Predicting California Demand Response: How do Customers React to Hourly Prices? Public Utilities Fortnightly, July 1, 2003. Available: http://www.americanenergyinstitutes.org/research/CaDemandResponse.pdf
5. Benefits of Demand Response in Electricity Markets and Recommendations for Achieving Them: A Report to the United States Congress Pursuant to Section 1252 of the Energy Policy Act of 2005. US Department of Energy, February 2006. Available: http://www.electricity.doe.gov/documents/congress_1252d.pdf

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Equations

Supply Curve

$$P_S(L)=a\cdot L^3+b\cdot L^2+\sum_{t=1}^{n}\{\delta_1\cdot c_t\cdot L+\delta_0\cdot d_t\}$$

Demand Curve

$$P_D(L)=\beta\cdot L^{1/E}$$

$$\beta=\frac{P_0}{L_0^{1/E}}$$

LSE Profit with Flat-Rate

$$\Pi_{LSE}=L_0\cdot(P_0-P_S(L_0))$$

Overall Price

$$R=L_{DA}\cdot P_{DA}+(L_{RT}-L_{DA})\cdot P_{RT}$$

Consumer Surplus Increase

$$\Delta CS=\int_{P^*}^{P_0}L(P_D)\partial P=\int_{P^*}^{P_0}\left(\frac{P_D}{\beta}\right)^E\partial P=\left(\frac{1}{E+1}\right)\left(\frac{P_D}{\beta}\right)^{E+1}\Bigg|_{P^*}^{P_0}$$

Producer Surplus Increase

$$\Delta PS=\int_{P_S(L_0)}^{P^*}L(P_S)\,\partial P=P^*L^*-P_0L_0-\int_{L_0}^{L^*}P_S(L)\,\partial L$$

$$\Delta PS=P^*L^*-P_0L_0-\int_{L_0}^{L^*}(aL^3+bL^2+cL+d)\partial L$$

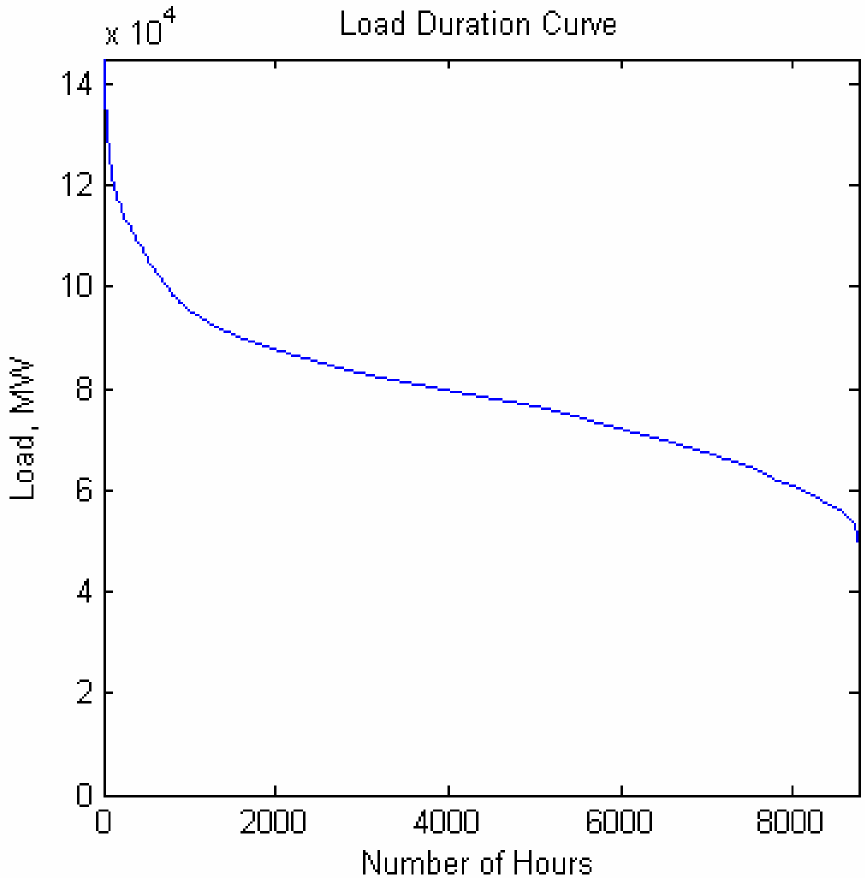
$$\Delta PS=P^*L^*-P_0L_0-\left[\left(\frac{a}{4}L^4+\frac{b}{3}L^3+\frac{c}{2}L^2+dL\right)\right]_{L_0}^{L^*}$$

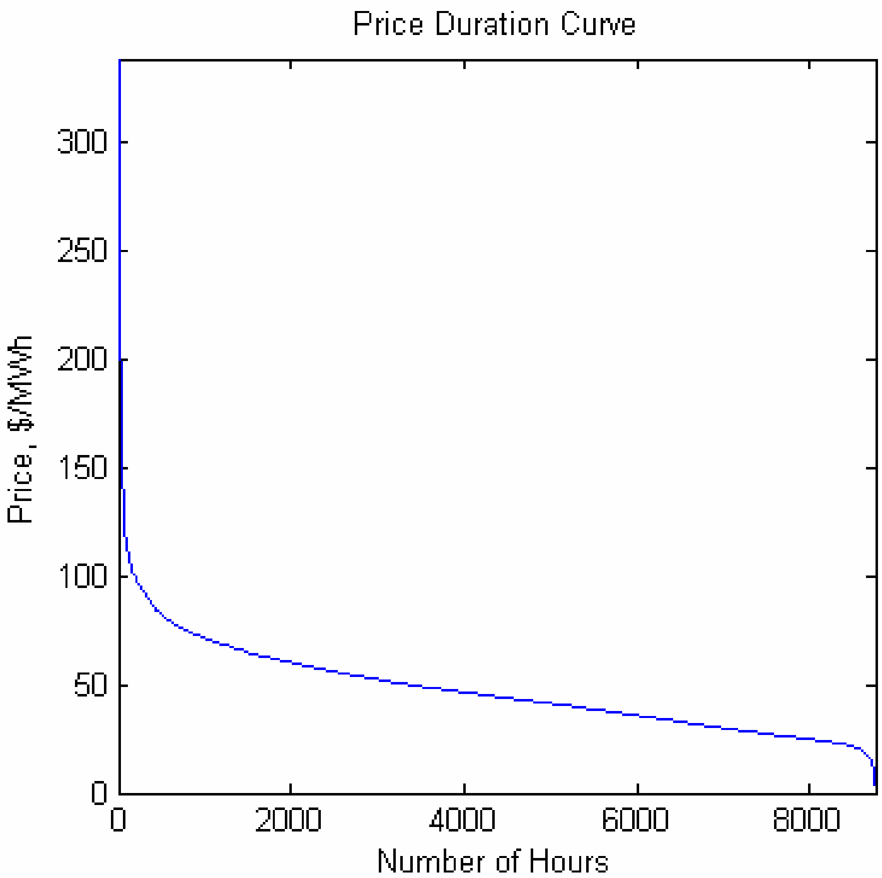
Deadweight Loss with Flat-Rate

$$DW_{flat}=\Delta\Pi_{flat}^{RTP}+\Delta CS_{flat}^{RTP}+\Delta PS_{flat}^{RTP}=\Delta CS_{flat}^{RTP}+\Delta PS_{flat}^{RTP}$$

$$DW_{TOU}=DW_{flat}-\Delta DW_{flat}^{TOU}=DW_{flat}-\left(\Delta CS_{flat}^{TOU}+\Delta PS_{flat}^{TOU}\right)$$

Load and Price Duration Curves





Model Fit and Significance

Overall Model Goodness of Fit and Statistical Significance		
F-Statistic	223	
p-value	0.000	
Adjusted R^2	0.949	
Parameter Significance p-values from t-test		
a	0.000	
b	0.000	
	mean	**median**
ct	0.000	0.008
dt	0.111	0.000

Adjusted R^2 for Other Models

Model From Best to Worst	Dummy Variables Included			
	1 δ_0	2 δ_0, δ_1	3 $\delta_0, \delta_1, \delta_2$	4 $\delta_0, \delta_1, \delta_2, \delta_3$
Day of Year	0.9096	0.9488	0.9630	0.9661
Week/WeekendorHoliday	0.8866	0.9124	0.9223	0.9241
Week/Weekend	0.8859	0.9118	0.9221	0.9240
Week of Year	0.8725	0.8961	0.9061	0.9079
Month of Year	0.8521	0.8774	0.8853	0.8887
Hour of Day	0.7990	0.8151	0.8208	0.8225
Day of Week	0.7942	0.8001	0.8085	0.8088
Year	--	0.6925	0.7453	0.7805

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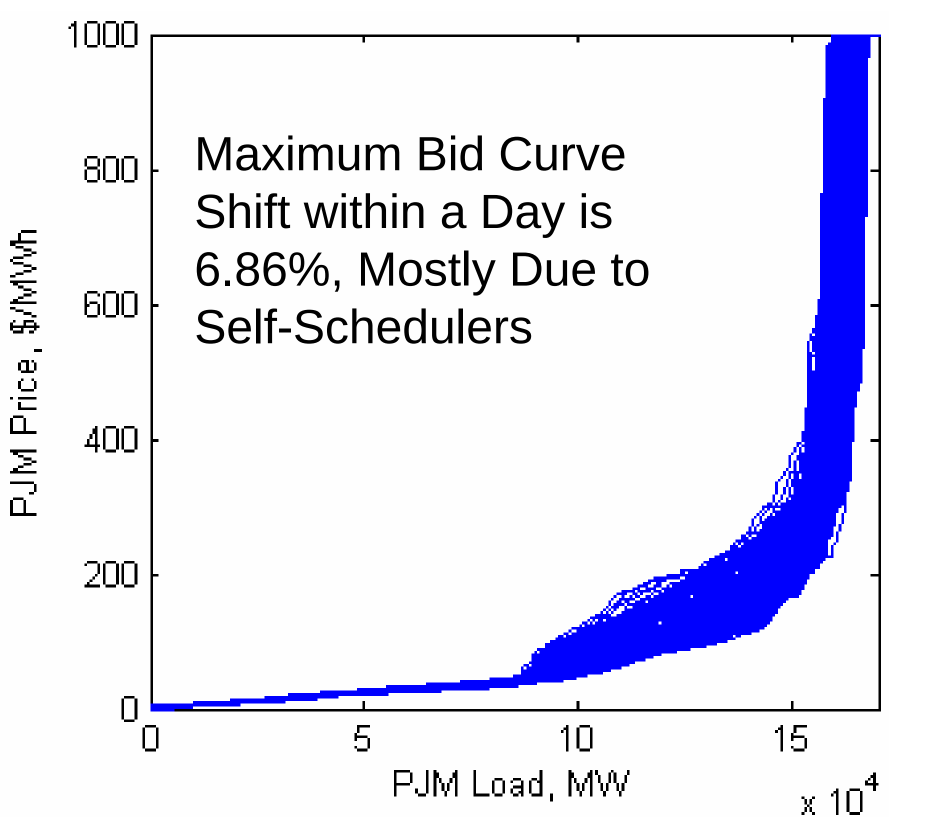
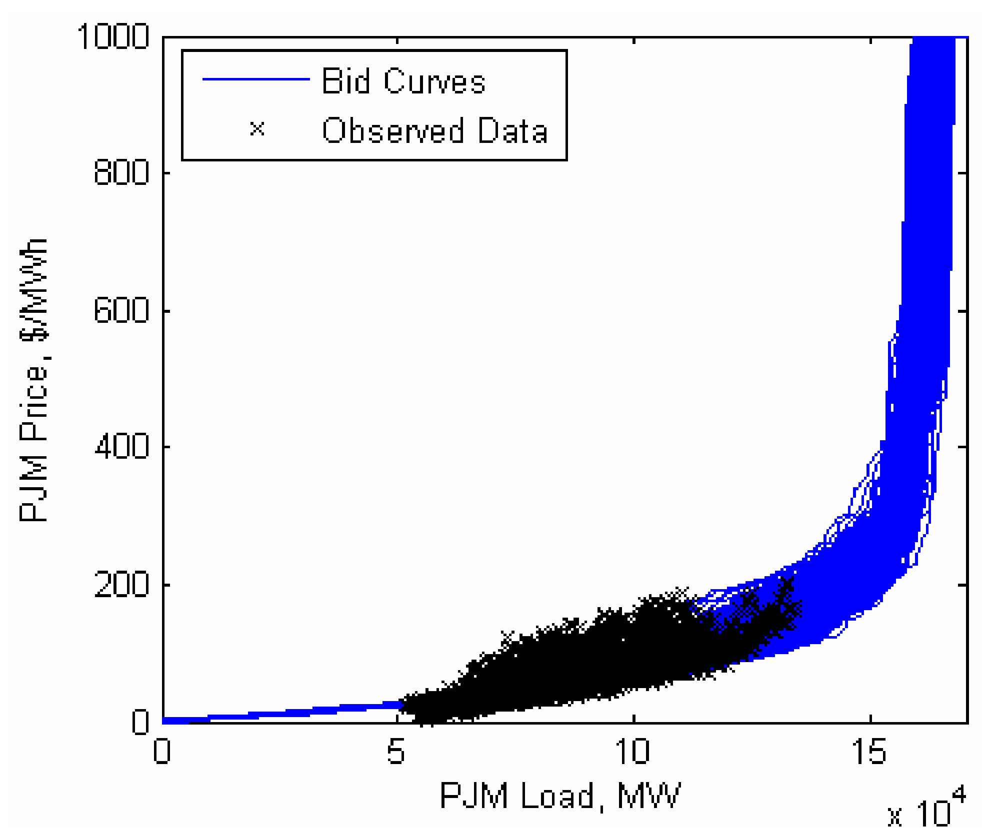
Stacked Marginal Cost Curve

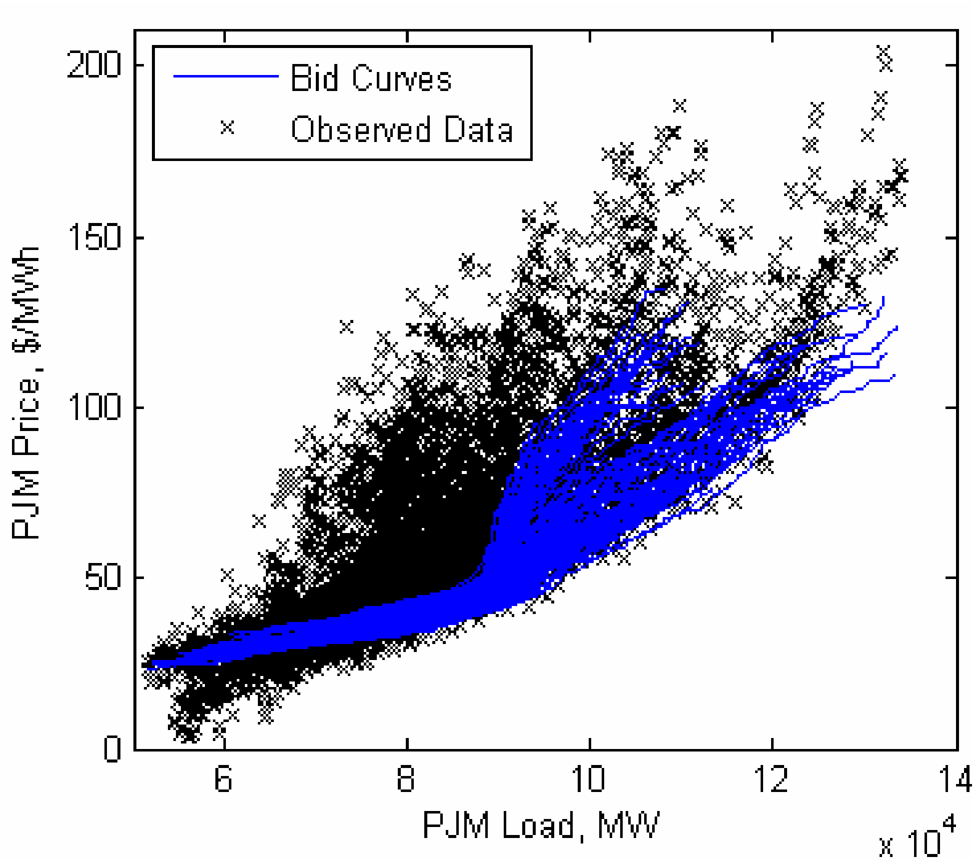
June 2005-May 2006 Noon Bid Curves



Bid Curves with Market Clearing Data



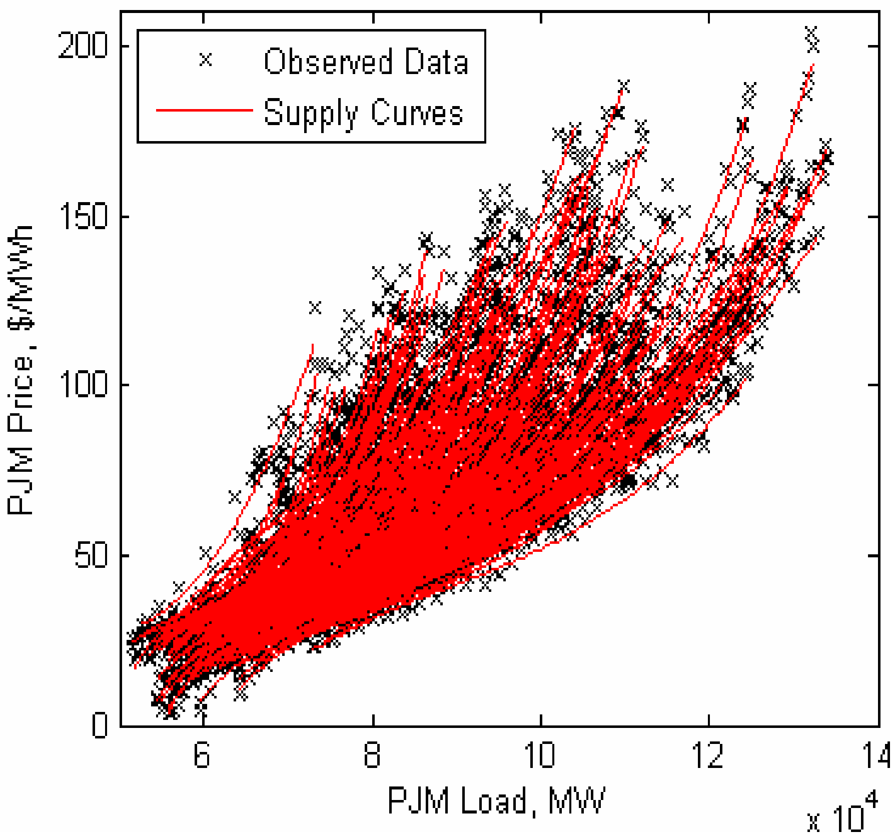
How Well do Bid Curves Represent Price?



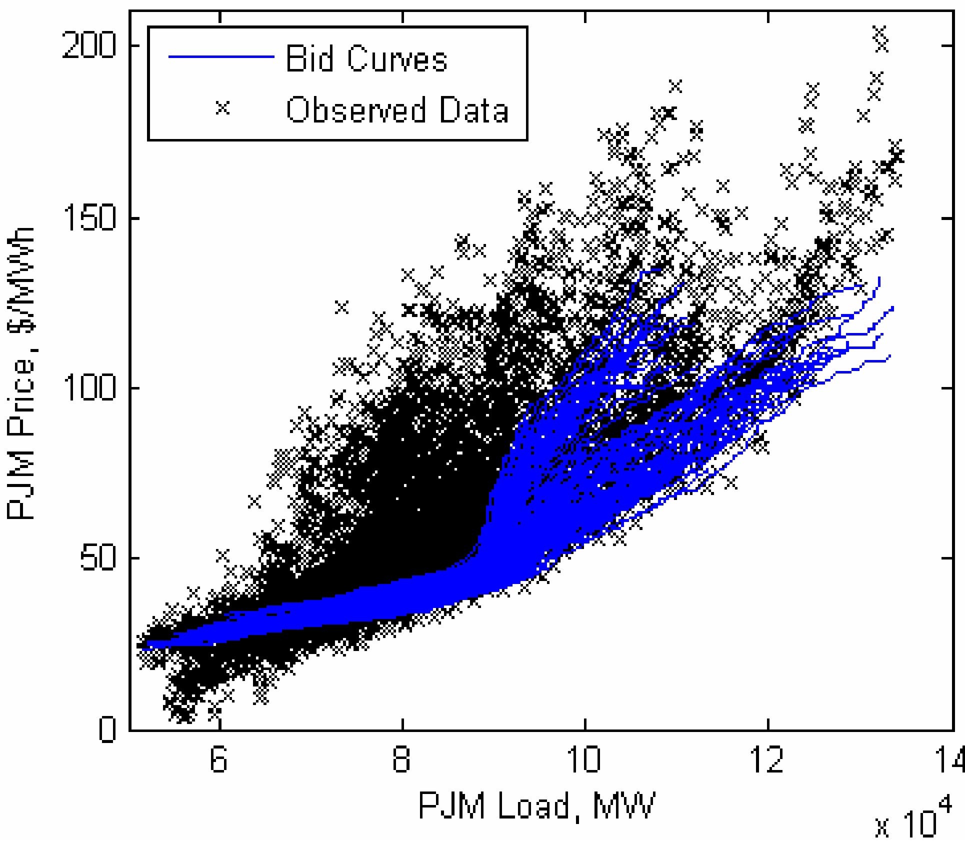
- Stacked generator bid curves underestimate price by $15.77/MWh on average

Supply Curves versus Bid Curves

Daily Supply Curves

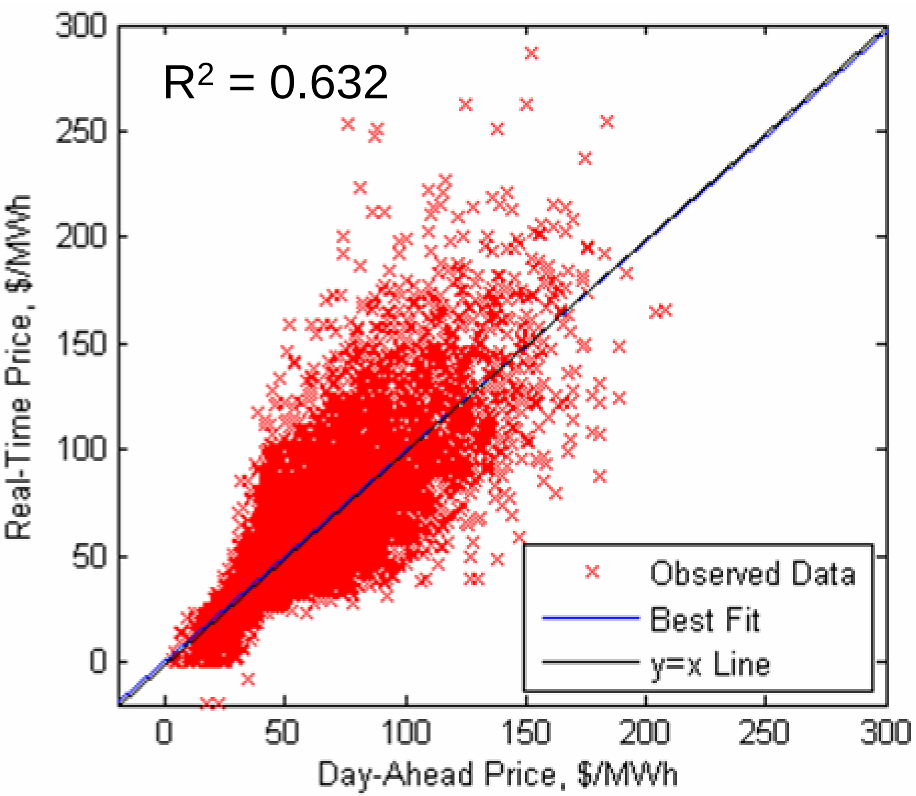


Daily Bid Curves

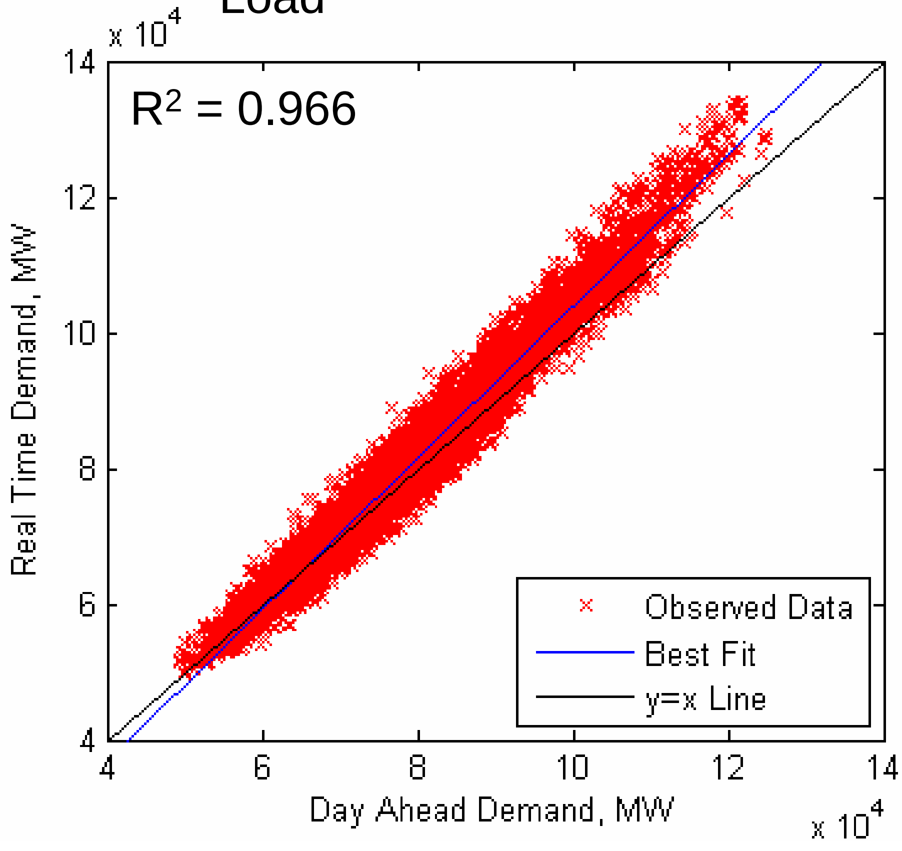


Real-Time vs Day-Ahead Prices and Loads

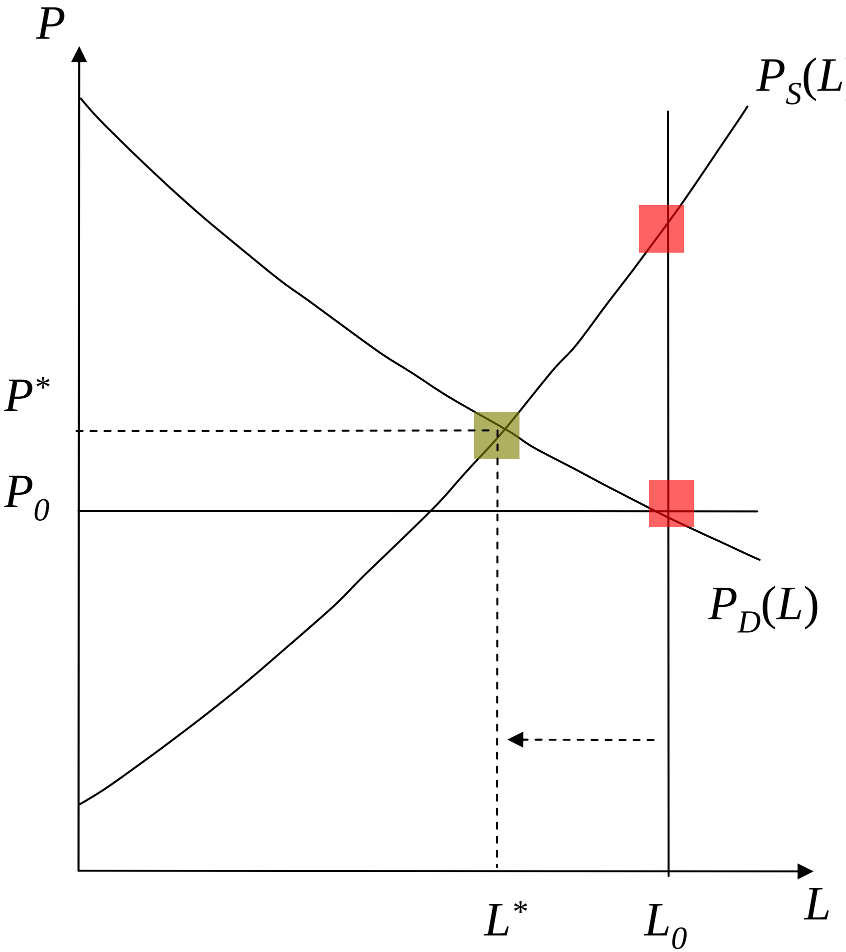
Price



Load



Demand Model



$$P_D(L) = \beta \cdot L^{1/E}$$

$$\beta = \frac{P_0}{L_0^{1/E}}$$

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End User Rates and Response Programs

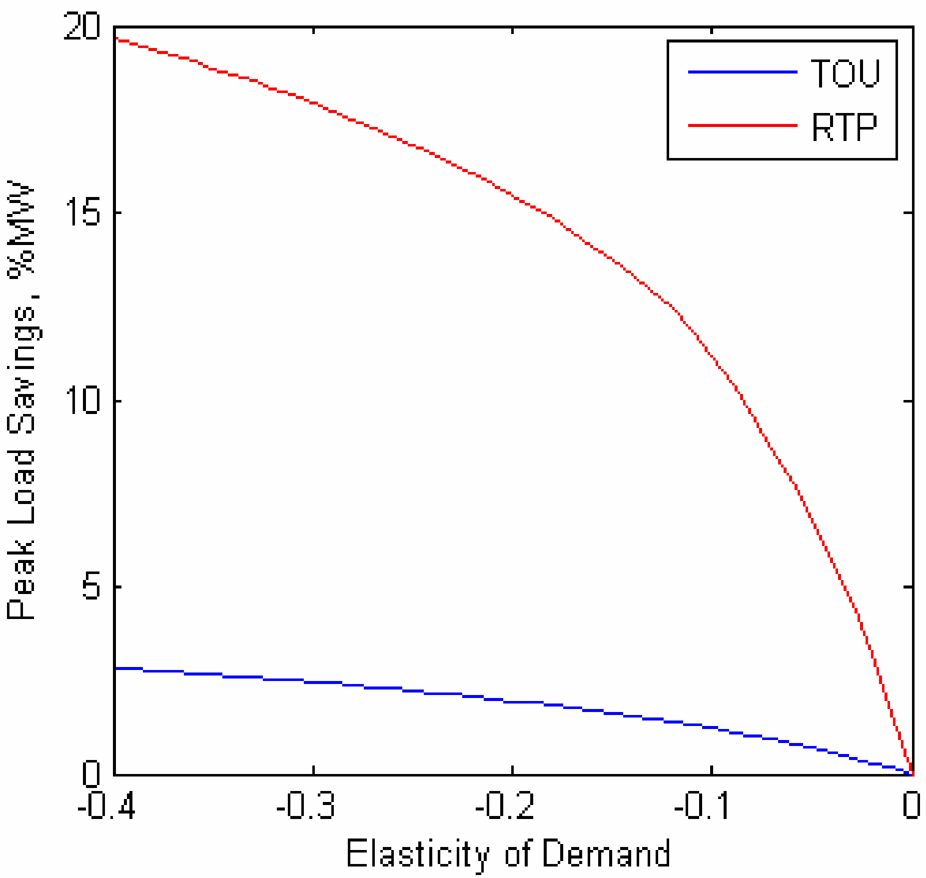
- PJM demand response programs, nonexclusive [a]
  - 4.1% of MW in at least one of three programs
  - Maximum reduction 0.2% of MW in Economic Program; 0.6% of MW in Active Load Management Program
- LSE Rates and Programs [a,b]
  - 1.3% of MW in a non-PJM load management program
  - 5.3% of MW on a rate “related” to LMP

[a] Assessment of PJM Load Response Programs. PJM Market Monitoring Unit. Report to the Federal Energy Regulatory Commission, Docket No. ER02-1326-006. August 29,2006. Available: http://www.pjm.com/markets/market-monitor/downloads/mmu-reports/dsr-report-2005-august-29-%202006.pdf

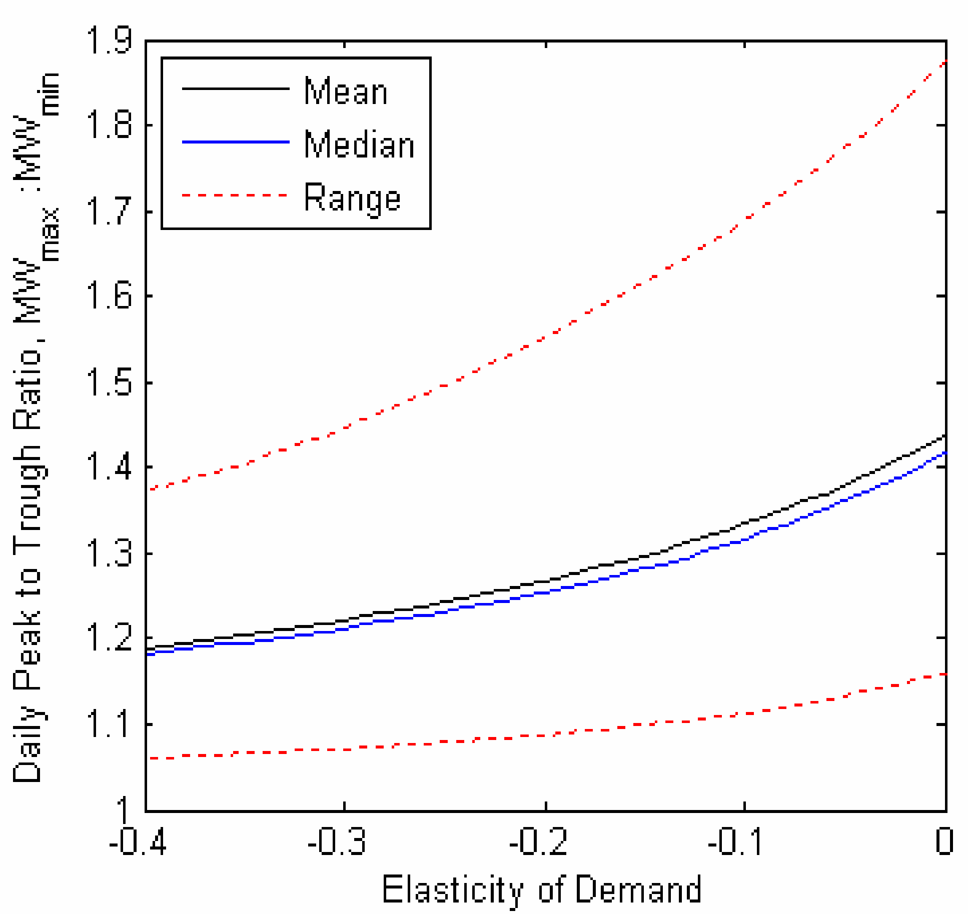
[b] *2005 Price Responsive Load Survey Results.* Available: http://www.pjm.com/committees/working-groups/dsrwg/downloads/20060615-05-price-responsive-load-survey.pdf

Peak Load Savings

Peak Load Savings

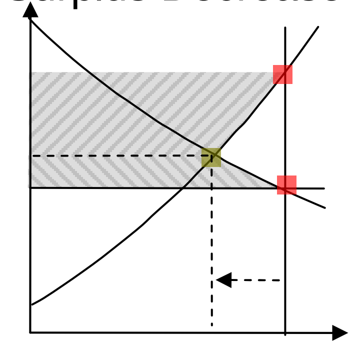


Moderated Load Cycling

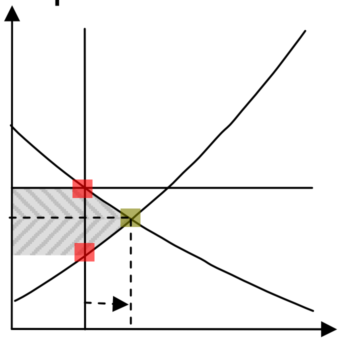


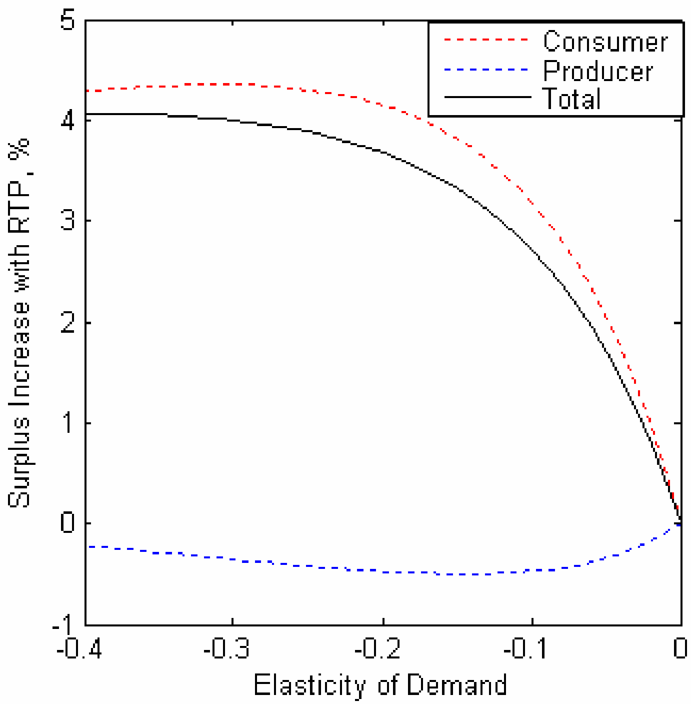
Total Surplus Increase

Surplus Decrease



Surplus Increase





Consumer Surplus Increase

$$\Delta CS = \int_{P^*}^{P_0} L(P_D)\,\partial P = \int_{P^*}^{P_0} \left(\frac{P_D}{\beta}\right)^{E} \partial P = \left(\frac{1}{E+1}\right)\left(\frac{P_D}{\beta}\right)^{E+1}\Bigg|_{P^*}^{P_0}$$

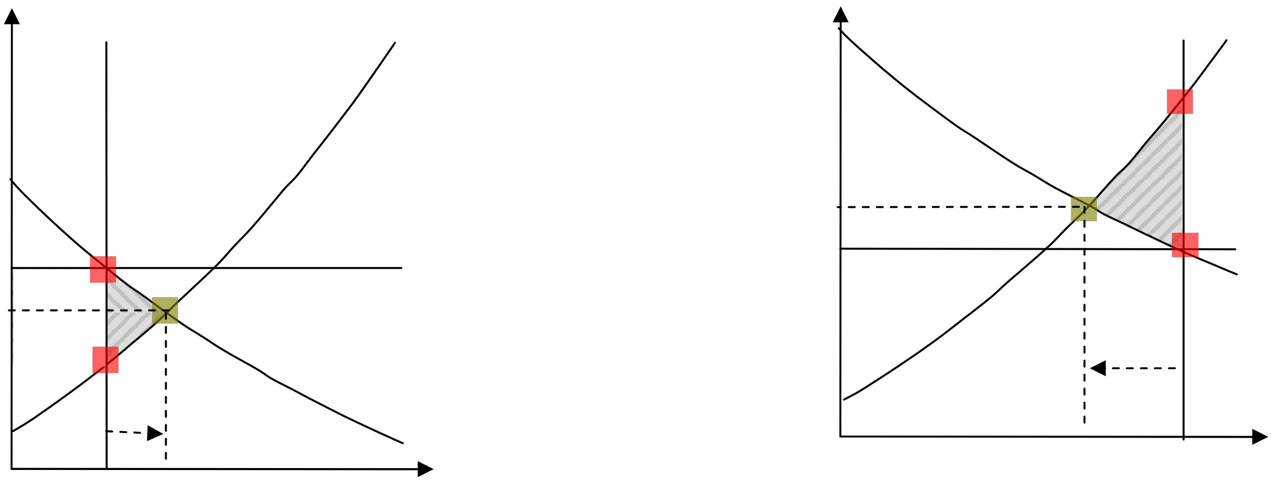
Producer Surplus Increase

$$\Delta PS = \int_{P_S(L_0)}^{P^*} L(P_S)\,\partial P = P^* L^* - P_0 L_0 - \int_{L_0}^{L^*} P_S(L)\,\partial L$$

$$\Delta PS = P^* L^* - P_0 L_0 - \int_{L_0}^{L^*} \left(aL^3 + bL^2 + cL + d\right)\partial L$$

$$\Delta PS = P^* L^* - P_0 L_0 - \left[\left(\frac{a}{4}L^4 + \frac{b}{3}L^3 + \frac{c}{2}L^2 + dL\right)\right]_{L_0}^{L^*}$$

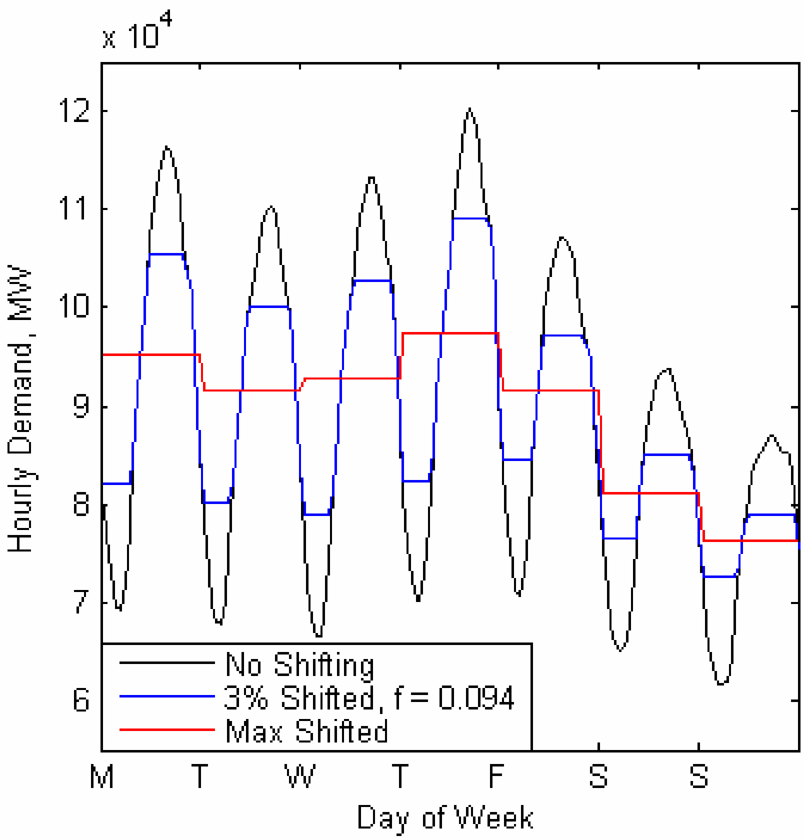
Flat-Rate DWL

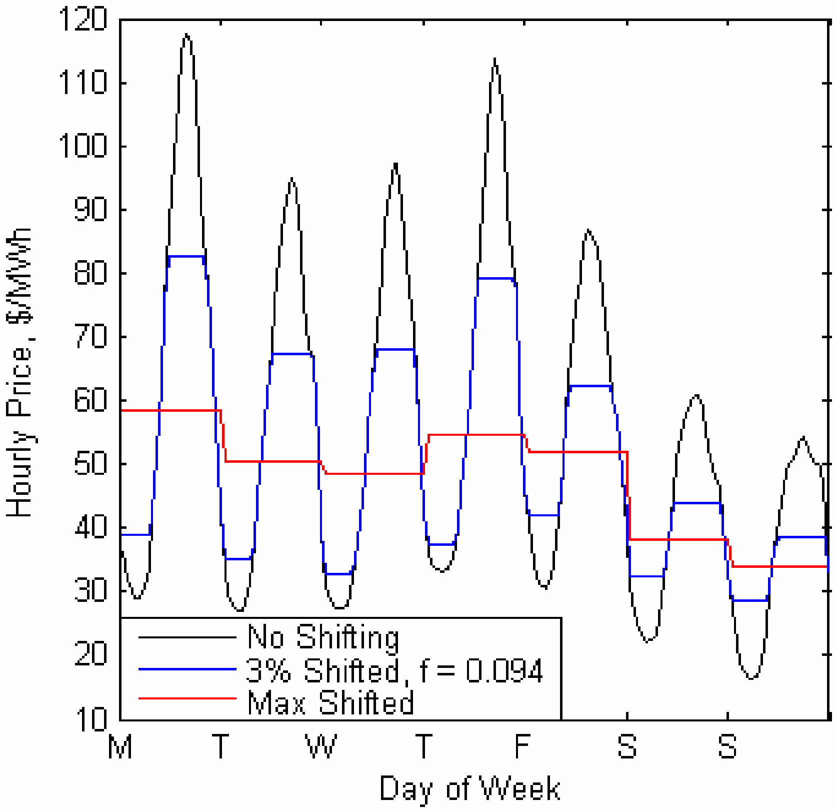


$$DW_{flat} = \Delta\Pi_{flat}^{RTP} + \Delta CS_{flat}^{RTP} + \Delta PS_{flat}^{RTP} = \Delta CS_{flat}^{RTP} + \Delta PS_{flat}^{RTP}$$

$$DW_{TOU} = DW_{flat} - \Delta DW_{flat}^{TOU} = DW_{flat} - \left(\Delta CS_{flat}^{TOU} + \Delta PS_{flat}^{TOU}\right)$$

Load Shifting Method





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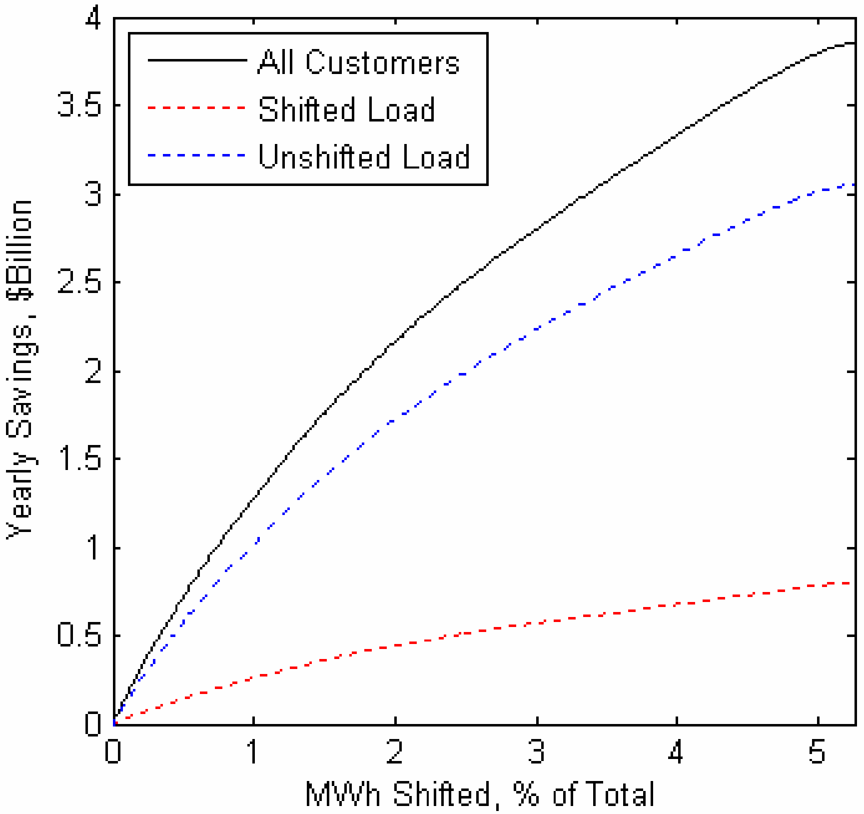
How Much Can Load Shifting Save Consumers? How Quickly?



% of Savings in Limit	% Load Shifted	Maximum Hourly % Curtailed
25%	0.70%	3.9%
50%	1.69%	6.6%
75%	3.15%	9.6%
90%	4.26%	12.4%
95%	4.66%	14.0%
99%	5.06%	16.5%

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