Electricity: Supply & Demand

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Bushnell,Mansur, Saravia. "Vertical Arrangements, Market Structure and Competition: An analysis of Restructured U.S. Electricity Markets." AER, (2008)

Reiss, White. "Household electricity demand, revisited." Restud (2005), Jessoe, & Rapson "Knowledge is (less) power: Experimental evidence from residential energy use" AER (2014), Ito "Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing" (2014)

Introduction & Question

- Antitrust policies concerns horizontal structure, but it comprises only one piece of the competition puzzle
- This paper empirically examines the relative importance of horizontal market structure and vertical arrangements in determining prices in imperfectly competitive markets.
- Three US electricity markets: California, New England, and the Pennsylvania, New Jersey, and Maryland (PJM) market.
- Address why there were apparent differences in the competitiveness of these markets.

Introduction & Question

- California electricity crisis made a perception that electricity markets are fundamentally different from other commodity markets.
- This paper demonstrates that fundamental concepts of oligopoly competition do apply to, and are significantly informative about, the restructured electricity industry.
- Reconstructs market conditions:
  1. calculate cost functions for the important market participants
  2. with data on firms' vertical commitments and hourly demand, simulate market outcomes under differing assumptions of firm behavior
  3. how markets are performing relative to the extremes determined by structural factors alone.

Literature

- Concern about the negative impacts of vertical arrangements:
    1. Foreclosure (impossible in electricity markets)
    2. Ability of integrated firm to raise rivals' costs (not applicable, ISO control the market)
    3. (this paper) Market performance.
- Rigidity of retail prices: regulators constrain retailers to adjust electricity prices (no more frequently than annually)
- Integrated firms are making retail price commitments before committing production to the wholesale market.

Results

- Vertical relationships: long-term price commitments to retail customers.
- Smaller position on the wholesale market
- Less incentive to raise wholesale prices
- Analogous to futures contract: are pro-competitive
- Firms undercut each other in forward market to gain a Stackelberg leader position

Results

- If not accounting vertical arrangements: eastern markets more competitive than Cournot
- When long-term arrangements included: Cournot equilibrium prices in markets fall
- So, actual prices are similar to Cournot behavior
- After accounting for these structural factors, there is relatively little variation between markets left to be explained by market rules, local regulation $\cdots$

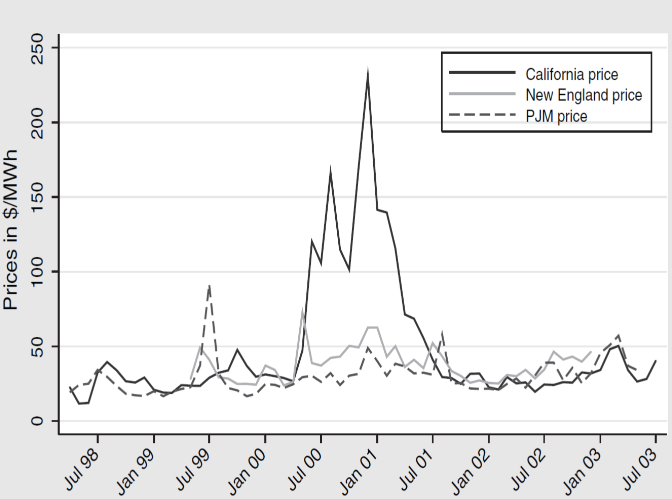
Results

- Long-term contracts and other vertical arrangements are a major source of differences in performance of electricity markets.
- If impeded vertical arrangements: prices higher + welfare loss + 45% increase in production costs

Electricity Markets' Structure and Design

- Large producers were granted authority to sell power at deregulated prices.
- Distribution and transmission sectors remain regulated
- Most utilities have retained ownership of transmission lines, but have relinquished the day-to-day control of the network to Independent System Operators (ISOs)
- ISOs operate electricity systems and provide market participants with equal access to the network.
- ISO spot, or "balancing" markets clear supply offers against inelastic demand

Price Path(monthly average)



Sample Period

- Introduce ISO and restructure in 1998
- Data:limited to June 1 to September 30,1999
- Was the initial high-demand period after all three markets were restructured
- Vertical arrangements of firms are exogenously determined in this period
- Stable market rules

Horizontal Structure

- PJM with a Herfindahl-Hirschman Index (HHI) of 1,400, is much more concentrated then either New England (850) or California (620).
- With a peak demand of 45,000 MW and similar installed capacity, California relies heavily on imports (25% import in 1999)
- New England, imports 10 %, older, gas- and oil-fired technology
- PJM using primarily coal, nuclear, and natural gas energy sources, no import.

Firm Characteristics for Each Market: Summer 1999

Firm	Fossil	Water	Nuclear	Other	Output max	Output share	Load max	Load share
Panel A: California firm characteristics								
PG&E	570	3,878	2,160	793	7,400	0.17	17,676	0.39
AES/Williams	3,921				3,921	0.09		
Reliant	3,698				3,698	0.08		
Duke	3,343				3,343	0.08		
SCE		1,164	2,150		3,314	0.08	19,122	0.42
Mirant	3,130				3,130	0.07		
Dynegy/NRG	2,871				2,871	0.06		
Other	6,617	5,620		4,267	16,504	0.37	9,059	0.20
Total	24,150	10,662	4,310	5,060	44,181		45,857	
Panel B: New England firm characteristics								
Northeast Util.	3,250	1,406	2,116	175	6,947	0.27	7,440	0.33
PG&E N.E.G.	2,736	915		165	3,816	0.15	4,440	0.20
Mirant	1,219			16	1,235	0.05		
Sithe	1,810				1,810	0.07		
FP&L Energy	965	365			1,330	0.05		
Wisvest	979				979	0.04	1,200	0.05
Other	4,722	1,095	2,495	1,319	9,595	0.37	9,281	0.42
Total	15,681	3,781	4,611	1,675	25,712		22,361	
Panel C: PJM firm characteristics								
Public Service Elec.	6,760		3,510		10,270	0.18	8,947	0.17
PECO	3,682	1,274	4,534		9,490	0.17	4,551	0.09
GPU, Inc.	7,478	454	1,513		9,445	0.17	7,602	0.15
PP&L Inc.	6,102	148	2,304		8,554	0.15	5,120	0.10
Potomac Electric	6,507				6,507	0.11	5,378	0.10
Baltimore G&E	3,945		1,829		5,774	0.10	5,792	0.11
Delmarva P&L	2,458				2,458	0.04	3,103	0.06
Edison	2,012				2,012	0.04		
Atlantic City Electric	1,309				1,309	0.02	2,224	0.04
Other	428	439			867	0.02	8,998	0.17
Total	40,681	2,315	13,690		56,686		51,715	

Retail Policies and Vertical Arrangements

- Regulators constrain firms' ability to adjust retail prices
- Following restructuring, incumbent utilities required to freeze retail rates for several years
- Retailers were vulnerable to wholesale price volatility, responded differentially across three markets.
- In PJM, retailers retained their generation assets.
- Vertical integration provided a physical hedge, so dampened wholesalers' incentive to set high prices

Literature on Regulation and Vertical Arrangement

- Some firms “net seller” while others “net buyers”
- Mansur (2007): a difference-in-differences approach.
- Using data from 1998 (regulated bidding) & 1999 (market-based bids)
- Mansur compares the changes in output quantities of net sellers with those of net buyers
- findings: two main net sellers produced relatively less during 1999 than during 1998 as compared to the other, net-buying firms.

Literature on Regulation and Vertical Arrangement

- In New England, to hedge their price exposure, retail utilities signed long-term supply contracts
- Bushnell and Saravia (2002) utilize bidding data to compare the bid margins of firms obligated to serve by not.
- Finding: bid margins from both classes of firms increase monotonically with overall market demand
- But that the margins of the "retailing" class of suppliers were often negative
- Indicating that these firms utilized their generation assets to lower overall market prices in hours when they were net buyers
- "monopsony" production strategies

Long-term Contract and Market Performance

- In contrast, the purchases of the utilities in California were notoriously concentrated in the spot markets
- During the summer of 1999, there were almost no meaningful long-term arrangements between merchant generation companies and the incumbent utilities.
- The largest utilities, Pacific Gas & Electric (PG& E) and Southern California Edison, did retain control of nuclear and hydrogeneration capacity
- Low marginal cost capacity limited the utilities' ability to exercise monopsony power
- The failure of the utilities to sign long-term contracts has been attributed to regulatory barriers (Bushnell (2004))

Method

- Examines the range of static-Cournot equilibrium price outcomes by different market structure
- Klemperer, Meyer (1989) develop a oligopoly competition in the electricity industry called supply function equilibrium (SFE)
- In many cases, there exist multiple SFE, are bounded by the Cournot and competitive equilibria
- Regulatory body determines which equilibrium

Model

- We first consider a general formulation of Cournot competition at the wholesale and retail levels

$$\pi_{i,t}(q_{i,t}, q^r_{i,t}) = p^w_t(q_{i,t}, q_{-i,t})\left[q_{i,t} - q^r_{i,t}\right] + p^r_{i,t}(q^r_{i,t}, q^r_{-i,t})q^r_{i,t} - C(q_{i,t})$$

- $q_{-i,t}$ quantity produced by other $N-1$ firms
- $q^r_{-i,t}$ retail supplied by other $N-1$ firms
- $p^w_t, p^r_{i,t}$ wholesale and retail market prices
- If $q_{i,t} - q^r_{i,t} < 0$
  - retail commitments could be larger than wholesale production
  - firm i is a net purchaser

Model

- Note both retail quantity and prices are fixed
- So, in F.O.C. both $p^r_{i,t}, q^r_{i,t}$ no derivative w.r.t. $q_{i,t}$

$$\frac{\partial \pi_{i,t}}{\partial q_{i,t}} = p^w_t(q_{i,t}, q_{-i,t}) + [q_{i,t} - q^r_{i,t}]\frac{\partial p^w_t}{\partial q_{i,t}} - C'_{i,t}(q_{i,t}) \geq 0$$

- The retail position of firm i plays the same role as a fixed-price forward commitment
- As the forward commitment increases toward the amount produced, the marginal revenue approaches the wholesale price.
- Cournot model with contracts close to $q_{i,t}$ is similar to the competitive outcome.

Model

- A supplier's retail commitment can be greater than its wholesale production
- The supplier wants to drive wholesale prices below competitive levels
- A larger degree of market power leads to lower prices
- Simulate three prices
  1. the perfectly competitive equilibrium
  $$p_t^w(q_{i,t}, q_{-i,t}) - C'_{i,t}(q_{i,t}) \geq 0$$
  2. Cournot equilibrium ignoring vertical arrangements (f.o.c. with $q^r_{i,t} = 0$)
  3. Cournot equilibrium that accounts for vertical arrangements (solve above f.o.c.)

Model

- The wholesale market price is determined from the firms' residual demand function (Q_t)
- Equals the market demand ($\bar{Q}_t$) minus supply from fringe firms
- Supply from imports & small power plants, q_t^{fringe}, so:

$$Q_t(p_t^w) = \bar{Q}_t - q_t^{fringe}(p_t^w)$$

Cost Functions-Fossil-Fired Generation Costs

- Explicitly model them based on reliable data on the production costs of thermal generation units
- direct fuel+environmental+variable operation and maintenance (VO&M) costs
- Fuel costs = "heat rate" (fuel efficiency) multiply price of fuel
- Environmental have to obtain nitrogen oxides & sulfur dioxide tradable pollution permits
- = emission rate (lbs/mmbtu) multiplied by price of permits and unit's heat rate.

Cost Functions-Fossil-Fired Generation Costs

- Capacity reduced by forced outage $(1 - fof_i) \times cap_i$
  - cap_i summer-rated capacity of the unit
- Firm-level production functions: a piecewise linear function of fossil fuel production costs
  - beginning at the marginal cost of its least expensive unit
  - ending at the marginal cost of its most expensive unit
  - perfectly inelastic at full capacity
  - shift rightward by the quantity of must-run (hydroelectric and nuclear) resources

Estimating Residual Demand

- Net of must-run and those with lax information
- Demand in wholesale electricity markets is completely inelastic
- $\Rightarrow$ residual demand curve = market demand - elastic supply of net imports (imports minus exports) -fringe plants not modeled
- Firms exporting into markets take prices as given (many of them)
- When transmission constraints not bind, one market

Estimating Residual Demand

- Proxy regional prices using daily temperature $Temp_{st}$
- Fixed effects for hour h of the day $Hour_{ht}$
- Day j of week Day_{jt}
- Estimate fringe supply q_t^{fringe} as a function of $ln(p_t^w)$
- Proxies for cost shocks $Month_{it}$
- Proxies for neighboring prices $Temp_{st}, Day_{jt}, Hourh_t$
- Idiosyncratic shock ε_t

$$q_t^{fringe} = \sum_{i=6}^{9} \alpha_i Month_{it} + \beta ln(p_t^w) + \sum_{s=1}^{S} \gamma_s Temp_{st} + \sum_{j=2}^{7} \delta_j Dat_{jt} + \sum_{h=2}^{24} \phi_h Hours_{ht} + \varepsilon_t$$

Estimating Residual Demand

- As price is endogenous, using two-stage least squares (2SLS)
- Instrument using the natural log of hourly quantity demanded inside each respective ISO system
- Because wholesale electricity demand is completely inelastic, instrument choice is valid
- 2SLS β (std) [implied elasticity] coefficients for hourly fringe supply for various functional form specifications of price

	$ln(Price)$	$Price$	$\sqrt{Price}$	$\sqrt[3]{Price}$
California	5,392.4*	124.8*	1,890.6*	5,164.3*
	(704.2)	(11.4)	(128.3)	(360.1)
	[−0.672]	[−0.463]	[−0.642]	[−0.665]
New England	1,391.1*	10.8*	308.5*	1,006.5*
	(162.3)	(3.2)	(53.4)	(148.2)
	[−0.168]	[−0.048]	[−0.113]	[−0.135]
PJM	860.7*	8.5*	220.2*	687.7*
	(118.3)	(2.4)	(42.9)	(117.1)
	[−0.027]	[−0.012]	[−0.023]	[−0.026]

Estimating Residual Demand

- Now determine N strategic firms' residual demand (Q_t)
- In equilibrium, $Q_t \sum_{i=1}^{N} q_i$ and α_i as vertical intercept

$$\alpha_t = \sum_{i=1}^{N} q_{i,t}^{actual} + \beta ln(p_t^{actual})$$

- Inverse residual demand:

$$p_t^w = exp\left(\frac{\alpha_t - \sum_{i=1}^{N} q_{i,t}}{\beta}\right)$$

Counterfactual Idea

- First set $q^r_{i,t} = 0$
- Counterfactual equilibria with incentive effects of vertical arrangements & long-term contracts are ignored
- Test the importance of vertical arrangements by $q^r_{i,t} =$ actual
- Structure and retail quantity is non-accurate

Drawbacks

- Marginal costs subject to measurement error
- Overstate MC, observed market prices during very competitive hours less than estimates
- MR independent of hour of day $\Rightarrow$ bias estimates of costs upward during off-peak, downward during peak
  - Because power plants have non-convex costs and intertemporal operating constraints (startup) limits change in production

Drawbacks

- Measurement of price
  - PJM market have many "nodal" prices for a given hour (paper uses a weighted average)
  - Average is noisy
  - However, prices did not vary substantially by location
- Cournot equilibrium can produce prices lower than perfectly competitive ones when vertical arrangements are considered
  - for large retailer profitable to decrease prices
  - when $q^r_{i,t} > q_{i,t}$ marginal revenue is greater than price
  - it is profit-maximizing to produce at levels where marginal cost is greater than price
- Thus, if load obligations ¿ production levels of key producers
- Cournot price "lower" bound, competitive price the "upper" bound.

Market-Level Results

- Table summarizes prices for Cournot equilibrium with and without vertical arrangements, competitive equilibrium, actual market prices
- Note that California market effectively had no long-term vertical arrangements
- There was considerable generation retained by the two largest, still partially vertically integrated, utilities
- So, no meaningful difference between a "no vertical arrangements" and "with vertical arrangements" case in California

Market-Level Results

- Errors in cost estimates large impact on estimates of competitive prices and Cournot prices than market power
- At low levels of demand, no market power, thus Cournot close to competitive prices
- When market power, quantity sensitive to slope of residual demand curve than to marginal costs
- Therefore separate results into peak & off-peak hours to reflect this differential impact of bias in cost measurement

Actual, Estimates of Competitive & Cournet Prices

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Panel A: Peak hours (11 am to 8 pm weekdays)					
California actual	43.15	34.52	27.0	17.2	225.0
Competitive	35.01	30.88	19.8	24.8	233.8
Cournot	45.17	40.19	21.0	25.2	233.8
New England actual	55.05	33.16	82.9	17.7	753.2
Competitive	41.72	35.04	33.9	29.7	333.3
Cournot	54.63	40.44	52.0	26.5	454.7
Cournot n.v.a.	280.47	145.86	298.3	50.3	1,000.0
PJM actual	97.31	33.17	210.2	11.2	999.0
Competitive	35.08	33.27	9.1	20.8	75.6
Cournot	87.05	36.00	171.8	22.7	1,000.0
Cournot n.v.a.	1,000.00	1,000.00	0.0	1,000.0	1,000.0
Panel B: Off-peak hours					
California actual	23.90	24.99	9.9	1.0	96.9
Competitive	26.10	27.44	6.4	1.2	50.3
Cournot	30.00	31.25	9.4	1.2	70.3
New England actual	29.18	26.61	37.9	1.0	1,000.0
Competitive	31.73	31.14	11.9	4.7	356.9
Cournot	32.63	30.54	18.7	4.7	481.3
Cournot n.v.a.	86.16	55.82	105.4	4.7	1,000.0
PJM actual	23.84	18.10	30.9	0.1	677.5
Competitive	25.42	23.78	6.3	16.4	52.7
Cournot	32.73	30.00	16.6	15.5	316.7
Cournot n.v.a.	900.57	1,000.00	261.2	31.2	1,000.0

Actual, Estimates of Competitive & Cournet Prices

Variable	Mean	Median	Standard deviation	Minimum	Maximum
Panel C: All hours					
California actual	29.69	27.99	19.1	1.0	225.0
Competitive	28.78	28.60	12.8	1.2	233.8
Cournot	34.56	33.60	15.6	1.2	233.8
New England actual	36.96	28.52	56.6	1.0	1,000.0
Competitive	34.73	32.06	21.6	4.7	356.9
Cournot	39.24	31.95	34.0	4.7	481.3
Cournot n.v.a.	144.56	67.28	206.0	4.7	1,000.0
PJM actual	45.92	20.99	122.8	0.1	999.0
Competitive	28.32	26.80	8.5	16.4	75.6
Cournot	49.06	31.27	98.4	15.5	1,000.0
Cournot n.v.a.	930.45	1,000.00	223.1	31.2	1,000.0

Market-Level Results

- In all three markets, actual prices consistent with Cournot than competitive, during peak
- California: actual \$43, Cournot \$45, competitive \$35
- New England: actual & Cournot \$55, competitive \$42
- PJM: actual \$97, Cournot \$87, triple competitive\$35.

Market-Level Results

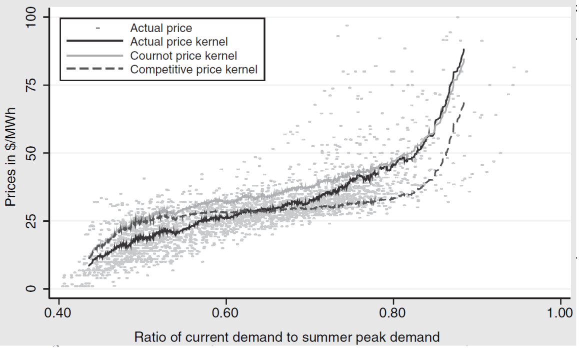
- Off-peak competitive price estimates exceed actual prices in all markets.
- California & PJM: low prices do not appear to be caused by monopsony behavior
  - because Cournot prices exceed the competitive prices even at low demand
- By contrast, negative price-cost, during off-peak in New England are consistent with strategic behavior
  - Cournot ($27) is below competitive price ($31) (actual $25)
  - only market where the dominant producers also have large retail obligations and sufficient extramarginal resources
  - This allows these firms to produce at a loss, on the margin, thereby reducing the equilibrium price.

Kernel Regression Results

- Estimate a nonparametric kernel regression of relationship between actual hourly prices and ratio of current demand to summer peak demand
- Non-parametric estimation of conditional expectation of a random variable
- For example Nadaraya-Watson estimator of m is $\hat{m_h}(x) = \frac{\sum_{i=1}^{n} K_h(x-x_i)y_i}{\sum_{i=1}^{n} K_h(x-x_i)}$
- K_h is a kernel with a bandwidth h
- Then the distribution is : $\hat{f}(x) = n^{-1}h^{-1}\sum_{i=1}^{n} K(\frac{x-x_i}{h})$

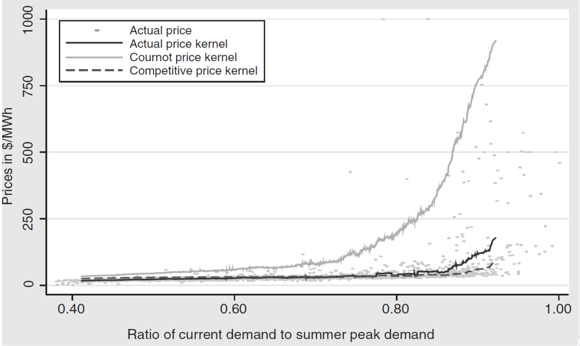
Kernel Regression Results-California

- California: Cournot estimates are similar, except at low demand levels,
- both competitive and Cournot prices exceed actual prices

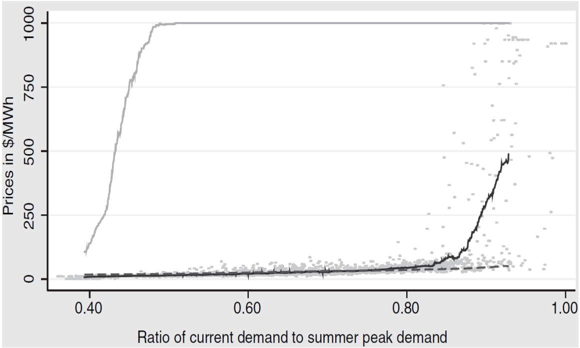


Kernel Regression Results-New England

- In both New England & PJM, Cournot (no vertical commitments) far exceed actual prices
- New England & PJM markets not oligopoly
- More competitive relative to CA (horizontal concentrated)

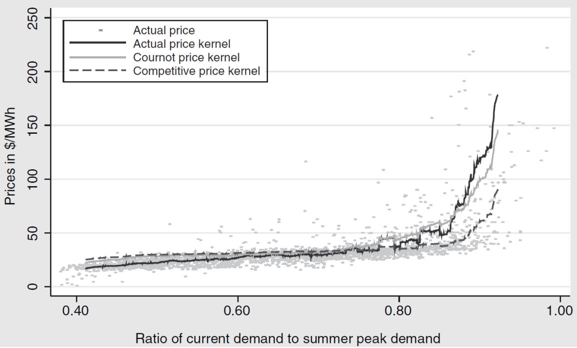


Kernel Regression Results-PJM



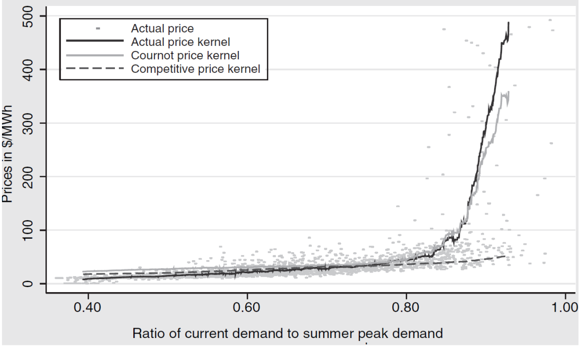
Vertical Arrangement New England

- If account for vertical arrangements
  - Cournot prices are similar to actual prices at high demand levels



Vertical Arrangement PJM

- As with California, the Cournot prices are similar to the actual prices at high demand levels.



Testing Market Performance

- We examine the relative goodness-of-fit of the two estimated price series to actual prices
  - Cournot with vertical arrangements
  - competitive
- A variation on the traditional R^2 to measure each model's fit

$$R^2 = 1 - \frac{\sum_{t=1}^{T} (p_t^{actual} - p_t^{sim})^2}{\sum_{t=1}^{T} (p_t^{actual})^2}$$

- p_t^{sim} is p_t^{cour} or p_t^{comp}

Testing Market Performance

- Always, Cournot greater measures of R^2 than competitive
- CA: R^2 Cournot 0.94, competitive 0.92
- New England: R^2 Cournot 0.82, competitive 0.69
- PJM: R^2 Cournot 0.78, competitive 0.18
- Similar for peak hours
- More formal test: regressing actual prices on Cournot & competitive

$$p_t^{actual} = \gamma_1 p_t^{cour} + \gamma_2 p_t^{comp} + u_t$$

Testing Market Performance

- OLS: corrected for heteroskedastic & autocorrelated errors
- Correct var-cov matrix to account for 1-stage uncertainty
- To be consistent with Cournot (strong test)
  1. cannot reject $\gamma_1 = 1 \quad , \gamma_2 = 0$
  2. can reject $\gamma_1 = 0 \quad , \gamma_2 = 1$
- For all three markets, the tests suggest that Cournot prices are a better fit for actual peak-hour prices than the competitive prices
- In addition to examining predicted prices, we compare the quantity decisions of firms

Social Welfare Impacts

- End-use demand is inelastic
- So, any social welfare impacts only from production costs.
- PJM (no vertical arrangements) produces prices at capped level (only consider no-capped cases)
- In PJM, production costs under vertical contracts are 59% lower than no-vertical
- In New England: 32%
- If they abandon vertical like CA, costs much higher
- PJM, not competitive, vertical arrangements critical in mitigating market power in spot market.

Stability of Vertical Structure

- Sample was early in divestiture. Are these vertical obligations likely to be stable?
- Forward market mitigate market power
- Vertical relationship is like forward market.
- Assumption: retail margins zero profit $\Rightarrow$ retail rates is expectations of wholesale prices

Stability of Vertical Structure

- Why they sell forward, to make a credible commitment to produce more in subsequent wholesale markets
  - thereby reaping advantages like leader in a Stackelberg game
- Examine unilateral optimality of a firm vertical position.
- We do so by marginally changing a given firm's vertical position, while holding the position of all other firms constant.
- Table describes the change in profits to each large firm in a market from an increase in forward position by the firm listed in the first column
- Diagonal are impact on profits of a given firm from its own increase in forward position

Stability of Vertical Structure

Panel A: Major California firms

	Base profits	Percent change				
		AES	Reliant	Duke	Mirant	Dynegy
AES/Williams	43.3	**5.8**	−4.4	−3.0	−3.4	−3.6
Reliant	46.3	−4.7	**5.5**	−2.9	−3.3	−3.6
Duke	28.9	−5.0	−4.4	**4.2**	−3.4	−3.7
Mirant	37.7	−4.9	−4.4	−3.0	**5.0**	−3.7
Dynegy/NRG	48.8	−4.4	−4.0	−2.8	−3.2	**5.0**

Panel B: Major New England firms

	Base profits	Percent change				
		NU	PG&E	Mirant	Sithe	FP&L
Northeast Util.	332.5	**−0.4**	−0.1	−0.3	−0.5	−0.2
PG&E N.E.G.	122.6	−0.4	**−0.3**	−0.4	−0.8	−0.3
Mirant	24.3	−0.3	0.0	**0.5**	−1.2	−0.5
Sithe	22.6	−0.2	0.0	−0.5	**0.6**	−0.5
FP&L Energy	32.2	−0.2	0.0	−0.4	−1.0	**0.3**

Panel C: Major PJM firms

	Base profits	Percent change					
		PSEG	PECO	GPU	PP&L	Potomac	BG&E
Public Service Elec.	553.8	**−1.7**	−1.0	−2.3	−2.2	−0.9	−0.3
PECO	577.7	−1.0	**−0.4**	−1.4	−1.3	−0.6	−0.2
GPU, Inc.	522.0	−1.6	−0.9	**−1.7**	−2.1	−0.9	−0.3
PP&L Inc.	427.2	−1.4	−0.8	−2.0	**−1.1**	−0.8	−0.2
Potomac Electric	265.8	−2.2	−1.3	−3.1	−2.9	**−1.2**	−0.3
Baltimore G&E	399.4	−1.5	−0.8	−2.0	−1.9	−0.9	**−0.2**

Stability of Vertical Structure

- In California would want to increase their positions above zero
- All the largest firms in PJM would prefer to reduce their positions.
- Indicates generation suppliers will continue to seek long-term retail commitments

Table of Content

Bushnell,Mansur, Saravia. “Vertical Arrangements, Market Structure and Competition: An analysis of Restructured U.S. Electricity Markets.” AER, (2008)

Reiss, White. ”Household electricity demand, revisited.” Restud (2005), Jessoe, & Rapson “Knowledge is (less) power: Experimental evidence from residential energy use” AER (2014), Ito “Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing” (2014)

Introduction

- Demand estimation important for non-linear tariff design and subsidy plan.
- Difficulties:
  - nonlinearities of tariff schedules
  - aggregation of consumption behavior over time and appliances
  - interdependence of energy use with longer-term household decisions over appliance ownership & dwelling characteristics

Introduction-Method

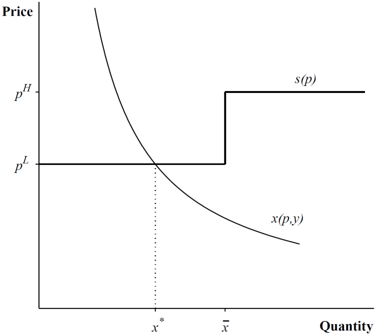
- Focus on heterogeneity in households' demand elasticities
- Their relation to appliance holdings
- How predict household consumption responses to (nonlinear) price schedule changes
- Use a standard model of endogenous sorting & a groupwise specification of price-sensitivity heterogeneity

Introduction-Contribution

- Following an electricity supply crisis in that state
- Regulatory approved a five-part tariff structure
  - induce energy conservation
  - raise additional revenue for utilities
  - minimize expenditure changes for lower-income households
- Use estimated demand model to examine the effects of tariff changes

Modeling Demand with Nonlinear Prices

- Nonlinear price schedules take the form of multi-part tariffs.
- Marginal price charges step-wise with quantity demanded
- Could be decreasing $\Rightarrow$ volume discounts



Modeling Demand with Nonlinear Prices

- Multi-part prices imply that the consumer faces a nonlinear (i.e., a kinked) budget constraint
- Demand behavior depends not on average, nor any single marginal price, but on the entire price schedule (Gabor (1955))
- The standard econometric approach is to "linearize" budget constraint
- Express demand under nonlinear pricing in terms of the ordinary demand function of classical consumer theory

Modeling Demand with Nonlinear Prices

- $x(p; y)$ be ordinary demand function with optimal consumption bundle $x^* = x(p^*, y^*)$
- p^*: slope of approximating linear budget constraint OR consumer's equilibrium marginal willingness-to-pay
- $y^* = y + \bar{x}(p^* - p^L)$ income level that would induce consumption x^*
- Both p^*, x^* are endogenously determined, according to the three-equation system
  1. non-linear demand
  2. expression for y^*
  3. nonlinear price schedule $s(p^*)$

Modeling Demand with Nonlinear Prices

- Marginal price is simultaneously determined by supply/demand
- OLS using p^* is biased and inconsistent
- How? exogenous proxy for the marginal price or instrumental variables procedures in estimation
- Proxy mis-specify marginal price
- IV difficult to find
- Need more sophisticated estimation methods.

Modeling Demand with Nonlinear Prices

- An alternative solve three equation system

$$x^* = \begin{cases} x(p^L, y) \quad if \quad x(p^L, y) < \bar{x} \\ x(p^H, y^H) \quad if \quad x(p^H, y^H) > \bar{x} \\ \bar{x} \quad if \quad otherwise \end{cases}$$

- where $y^H = y + \bar{x}(p^H - p^L)$
- By solving this no need for IV or proxy

Stochastic Specifications and Expected Consumption

- Demand is typically as $x(p, y, z, \varepsilon)$
- z: observed consumer characteristics,ε stochastic term
- In a structural model, stochastic term reflects unobservable heterogeneity.
- Consumer knows ε, but econometrician treat it as random

Stochastic Specifications and Expected Consumption

- Probability distribution of ε show how willingness-to-pay varies in the population
- In multi-tariff, marginal price is self-selected
- This selection induces correlation between marginal price and stochastic term
- Low ε low tarrif, and vice versa
- Must account for consumer's willingness to switch tariff when integrating out the unobservables.

Stochastic Specifications and Expected Consumption

- Handling these complications requires explicitly modeling the selection behavior

$$x(p, y, x; \beta) + \varepsilon$$

- Optimal consumption level is

$$x^* = \begin{cases} x(p^L, y, z; \beta) \quad if \quad \varepsilon < c_1 \\ \bar{x} \quad if \quad c_1 < \varepsilon < c_2 \\ x(p^H, y^H, z; \beta) \quad if \quad \varepsilon > c_2 \end{cases}$$

- where $c_1 = \bar{x} - x(p^L, y, z; \beta)$ and $c_2 = \bar{x} - x(p^H, y^H, z; \beta)$

Stochastic Specifications and Expected Consumption

- Assume state variables $\omega = \{p^L, p^H, \bar{x}, y, z\}$

$$\begin{aligned} E(x^*|\omega) = & [x^L(\beta) + E(\varepsilon|\varepsilon < c_1(\beta), \omega)]P(\varepsilon < c_1(\beta)) \\ & + \bar{x}P(c_1(\beta) < \varepsilon < c_2(\beta)) \\ & + [x^H(\beta) + E(\varepsilon|\varepsilon > c_2(\beta), \omega)]P(\varepsilon > c_2(\beta)) \end{aligned}$$

- P conditional probability of ε given ω
- $x^H(\beta) \equiv x(p^H, y^H, z; \beta)$ and $x^L(\beta) \equiv x(p^L, y, z; \beta)$

Stochastic Specifications and Expected Consumption

- Assume normal distribution

$$E(x^*|\omega) = [x^L(\beta) - \sigma\lambda_1]\Phi_1 + \bar{x}(\Phi_2 - \Phi_1) + [x^H(\beta) + \sigma\lambda_2](1 - \Phi_2)$$

- $\lambda_1 \equiv \phi_2/\Phi_1$ and $\lambda_2 \equiv \phi_2/(1 - \Phi_2)$
- ϕ_1 and ϕ_2 evaluated at $c_1(\beta)/\sigma$ $c_2(\beta)/\sigma$

Modeling Note

- Consumer's marginal price is related to ε, changes endogenously as ε varies
- Similar to the sample-selection models,
- Terms in square brackets are essentially "Heckit"-style conditional expectation functions
- unobservables of consumers with lower MR are different than those who choose the higher-tier price
- This framework is easily generalized to more complex tariff structures

Household Electricity Demand

- Demand for electricity is derived from services by durable energy-using appliances
- A useful distinction between short-run and long-run demand elasticities
- "Short-run" refers to demand behavior taking existing appliance stock as given
- In contrast, long-run elasticities incorporate both changes in utilization and adjustments to appliances
- This paper only short-run and utilization

Household Electricity Demand

- Electricity consumption is not recorded at the level of the individual appliance
- Each of a household's individual appliances as a latent outcome.
- Then aggregate these appliance-level demand specifications to obtain household electricity demand

$$x_k = \alpha_k p + \gamma_k y + z_k' \delta_k + \varepsilon_k$$

- appliance type $k = 1, 2, \cdots, K$

Household Electricity Demand

- Household electricity

$$x = \sum_{k=1}^{K} d_k x_k$$

- $d_k = 1$ if household owns appliance type k,so

$$x = \sum_k d_k \alpha_k p + \sum_k d_k \gamma_k y + \sum_k d_k z_k' \delta_k + \sum_k d_k \varepsilon_k$$

- or $x = \alpha p + \gamma y + z' \delta + \varepsilon$
- which $\alpha = \sum_k d_k \alpha_k$

Household Electricity Demand

- Not estimate α rather $\alpha_1, \alpha_2, \cdots, \alpha_K$
- So, elasticity depends on portfolio of appliances
- ε is heteroscedastic
- because variance of household-level stochastic term depends upon which appliances are held by individual

$$var(\varepsilon) = \sum_{j=1}^{K} \sum_{k=1}^{K} d_j d_k cov(\varepsilon_j, \varepsilon_k) \equiv \sigma(d_1, d_2, \cdots, d_K)^2$$

Aggregation over Time

- Multi-part tariffs apply on a monthly basis
- Data only annual household electricity consumption
- This temporal mismatch creates a potential source of aggregation bias
- Household may choose to consume at different prices during different times of the year.
  - weather-sensitive appliances are energy-intensive, push onto a higher tariff
  - seasonal tariff changes always exists
- With nonlinear prices the bias worsen
- So, aggregation must be modeled explicitly

Aggregation over Time

- A second issue: effect of weather & other time-varying covariates
- Need information on time-varying covariates change during the year
- Paper uses location-specific monthly weather/rate information
- treating unobserved monthly consumption outcomes as latent variables
- ω_t observable variables affecting the household's consumption t

Aggregation over Time

- x^* household's electricity consumption in month t
- $x^a = \sum_{t=1}^{12} x_t^*$ household's annual electricity consumption.

$$E[x^a|\omega_1, \omega_2, \cdots, \omega_1 2] = \sum_{t=1}^{12} E[x_t^*|\omega_t]$$

- Additive separability of the conditioning sets assumption
- Restrict household substitution behavior overtime
- Assume households consume electricity out of annual income.
- Only time-varying elements weather-related covariates
- Non-storable so just function of that month weather

Estimation Method

- Poor identification, because for some realizations, conditional expectation is nearly flat w.r.t σ
- To resolve, incorporate information on higher moments of model into estimation.
- So, generalized method of moments (GMM) procedure 1st & 2nd moments of annual consumption
- $h_r(\Omega, \theta) = E[(x^a)^r|\Omega]$ r-th conditional moment of annual consumption
- θ set of unknown parameters, $\Omega = \{\omega_1, \omega_1, \cdots, \omega_{12}\}$

$$u_1 = x^a - h_1(\Omega, \theta)$$
$$u_2 = (x^a)^2 - h_2(\Omega, \theta) - 2h_1(\Omega, \theta)(x^a - h_1(\Omega, \theta))$$

Estimation Method

- By construction, both mean u_1 and u_2 =0 given Ω
- Cross-product term (in u_2) added to improve estimator
- h_2 requires an assumption about correlation of ε over time
- Assumed independent from month to month
- Optimal instruments involve (covariance-weighted) derivatives of the conditional moments.(β for demand ζ for variance)

$$z_1(\Omega, \theta)' = \bigtriangledown_\beta h_1(\Omega, \theta)$$

$$z_2(\Omega, \theta)' = \begin{pmatrix} \bigtriangledown_\beta h_2(\Omega, \theta) \\ \bigtriangledown_\zeta h_2(\Omega, \theta) \end{pmatrix}$$

Estimation Method

- The unconditional orthogonality conditions are then $E[z_r' u_r] = 0, \quad r = 1, 2$
- $m = 2dim(\beta) + dim(\zeta)$ moment equations
- Note that the gradient of h_1 with respect to the variance parameters is excluded from the instruments
- h_1 contains no useful information (singular)
- This is the reason the variance parameters are poorly identified by nonlinear least squares estimation using the first moments alone

Estimation Method

- Estimator minimizes $||Au(\theta)||^2$, A is an $(m \times 2n)$ weighting matrix (fixed during minimization)

$$u(\theta) = \begin{bmatrix} u_1(\theta) \\ u_2(\theta) \end{bmatrix}$$

- The matrix $A = \tilde{R}\tilde{Z}'D$
  - D is a diagonal matrix containing the appropriate survey sampling weight for each observation
  - $\tilde{Z}$ is the $(2n \times m)$ matrix of instruments evaluated at an initial consistent estimate of θ
  - $\tilde{R}$ is the (upper) Cholesky factor of an approximation to the inverse moment covariance matrix.
  - Specifically, $\tilde{R}'\tilde{R} = [D\tilde{Z}'\tilde{\Psi}\tilde{Z}D]^{-1}$
  - $\tilde{\Psi}$ is an estimate of the covariance matrix $\Psi = E[u(\theta)u(\theta)'|\Omega]$
  - 270 moments and 212 parameters

Data and Empirical Specifications

- Data: Residential Energy Consumption Survey (RECS)
- They use the California subsamples of the 1993 and 1997 survey waves
- 1,307 California households
- In-home interview on household's appliances, physical characteristics, demographic information
- Energy consumption data from local electric utility
- Two shortcomings of RECS data
  1. annual consumption but should be monthly
  2. limited electricity tariff information available in the survey

Prices in Data

- California: two-tier electricity price schedule
- Schedules vary by service provider, climate zone, household heating system, household income, and season
- PG&E had 72 $(= 2 \times 2 \times 2 \times 9)$ standard residential schedules
- RECS only provides:
  - household's annual average electricity price
  - local electric utility's annual average revenue

Prices in Data

- Paper matches observations in RECS with actual schedules
- For matching RECS provides:
  - local utility's average electricity price (find provider)
  - availability and price of natural gas (find provider)
  - weather information (find climate zones)
  - household's income (find schedule)
  - home heating system (find schedule)
- 1,307 California households in the RECS sample matched to 189 distinct rate schedules.

Goodness of Matching, Stats Data and Actual

	Average Residential Rate in 1993[a] (cents per KWh)	*Number of Households*		*Percent of Househo*	
		Actual[a]	Estimate[b]	Actual[a]	Estimat
Investor-Owned Utilities					
Pacific Gas & Elec.	12.25	3,748,831	4,069,268	34.8	36.6
Southern Calif. Edison	12.10	3,636,295	3,655,184	33.8	32.9
San Diego Gas & Elec.	10.81	1,005,257	1,020,010	9.3	9.2
PacificCorp (Calif.)	6.94	31,872	351,053	0.3	3.2
Sierra Pacific Pwr. (Calif.)	8.79	36,581	169,317	0.3	1.5
Investor-Owned Subtotal		8,458,836	9,264,832	78.5	83.3
Municipal/Public Utilities					
Los Angeles	9.85	1,168,229	1,169,431	10.8	10.5
Sacramento	7.65	416,364	377,054	3.9	3.4
Riverside	10.57	80,828	35,510	0.8	0.3
Imperial	8.36	67,021	7,592	0.6	0.1
Santa Clara	7.30	38,129	126,735	0.4	1.1
Lompoc	9.21	12,729	61,569	0.1	0.6
Plumas-Sierra	7.70	4,674	82,557	0.0	0.7
Subtotal		1,787,974	1,860,448	16.6	16.7
Other Municipal/Public Utilities[c]		526,480	0	4.9	0.0
State Total		10,773,290	11,125,280	100.0	100.0

Appliance Demand Specifications

- Appliance demand: modeled end-use electricity demand using eight distinct appliance categories:
  1. Baseline electricity use
  2. Electric space heating
  3. Central air conditioning
  4. Room air conditioning
  5. Electric water heating
  6. Swimming pools
  7. Additional refrigerators and freezers
  8. Other appliances.
- Baseline category: universally owned (refrigerator and lights)
- Two-six are energy-intensive, with price elasticity (EPRI (1989))

Description of Appliances

Mnemonic	*Appliance*	*Description*
	Primary electric space heating	1 if household has permanently-installed electric space heating (electric furnace, heat pump(s), or wall resistance units)
	Central air cond.	1 if household has a central air conditioning unit
	Room air cond.	1 if household has room window/wall air conditioning units
	Electric water heat	1 if household has an electric water heater
ELECCOOK	Electric cooking	1 if household has an electric oven and/or stove
ELECDRYR	Electric dryer	1 if household has an electric clothes dryer
FREEZER1	Separate freezer	1 if household has a separate (stand-alone) freezer
FREEZER2	Second freezer	1 if household has two (stand-alone) freezers
FRIDGE2	Second refrigerator	1 if household has a second refrigerator
CLTHWASH	Clothes washer	1 if household has an automatic clothes washer
DISHWASH	Dish washer	1 if household has an automatic dish washer
PORTHEAT	Portable space heat	1 if household has one or more portable electric space heaters
HOTTUB	Hot tub	1 if household has a hot tub with electric heating
POOL	Swimming pool	1 if household has a swimming pool
H2OBEDHT	Waterbed heating	1 if household has a water bed with electric heating
MICROWV	Microwave	1 if household has a microwave oven
NTV	Number of TVs	Number of televisions in household

Demographic and Other Explanatory Variables

Mnemonic	*Variable*	*Description*
PRICE	Electricity price	Monthly electricity price, in 1993 cents per kilowatt-hour
INCOME	Household income	Average monthly household income, in thousand 1993 dollars
HDD	Heating degree days	Monthly heating degree days base 60°F, in hundreds
CDD	Cooling degree days	Monthly cooling degree days base 70°F, in hundreds
NROOMS	Number of rooms	Number of rooms in home (excluding bathrooms)
NBATHRMS	Number of bathrooms	Number of bathrooms in home
NMEMBERS	Number of members	Number of people in household
FRSIZE	Fridge/freezer size	Size of appliance, in cubic feet
ATHOME	At home	1 if someone is normally at home during the day
HUPROJ	Housing project	1 if household resides in a public housing project
APTBLDG	Apartment building	1 if household resides in an apartment building
RURAL	Rural location	1 if household resides in a rural location
URBAN	Urban location	1 if household resides in an urban location
YEAR97	Survey year 1997	1 if household data from 1997 survey wave

Estimates and Marginal Effects

- Next table: electricity demand coefficients
- Each column contains estimates associated with an appliance
- Mean square error is 2,352 KWh/year (1/3 of sample var)
- nonlinear GMM procedure so difficult to interpret estimates
- So, table entries show the marginal effect of a one unit increase in each explanatory factor on monthly kilowatt-hour consumption of each specified appliance.
- Weighted average across households using marginal effects for each household (gradient conditional expectation)

Estimated Marginal Effects

	Effect on KWh consumed per month for:[a]					
Explanatory Variable	*Baseline Use*	*Elec. Space Heating*[b]	*Central Air Cond.*[c]	*Room Air Cond.*[c]	*Elec. Water Heating*	*Swimming Pool*
Price (cents/kwh)	0.4	−37.8	−22.5	−63.4	−34.0	−27.5
	(3.7)	(14.8)	(21.3)	(31.1)	(9.5)	(18.4)
Income ('000 $)	0.4	16.2	9.1	21.6	−32.8	6.3
	(2.3)	(13.0)	(10.6)	(20.8)	(7.5)	(9.8)
N. Members	18.0	−7.9	−38.6	−52.1	47.5	
	(3.3)	(20.3)	(16.3)	(19.9)	(10.6)	
N. Rooms	12.9	20.4	9.8	29.2	−35.3	
	(4.5)	(22.0)	(17.4)	(23.4)	(15.2)	
N. Bathrooms	27.0				119.	
	(9.8)				(40.1)	
Heating Deg. Days ('00 °F, base 60)	−10.6	43.3				
	(6.3)	(21.9)				
Cooling Deg. Days ('00 °F, base 70)	−59.5		233.	45.1		
	(22.5)		(57.0)	(123.)		
Dummy Variables						
Apt. building	−48.4					
	(14.1)					
Housing project	−78.9					
	(24.6)					
At home during day	15.8					
	(10.0)					
Urban location	−35.5					
	(11.9)					
Rural location	31.4					

Price and Income Estimates

- Estimated price effects vary substantially across appliances
- The smallest effect is associated with baseline use, and is effectively zero
- All other appliance price sensitivities are of considerable practical significance
- Income effects are mostly statistically insignificant
  - because analysis is conditional on households' appliance stocks.

Variance Estimation

- 154 variance & covariance parameters
- Variance of household-level unobservable characteristics increases with appliance holdings
- Estimated standard deviation for baseline electricity consumption 387 KWh per month
- If electric space heating added, standard deviation of 479 KWh per month
- If further add central air conditioning & electric stove , it increases to 590 KWh per month

Price Elasticities

- Elasticities: percent change in a household's annual electricity consumption resulting from a one percent increase in marginal price
- Weighted average of 1037 household demand elasticities
- Mean annual electricity price elasticity for California =-0.39
- Same data, elasticity estimates obtained using OLS with average price: -0.28
- Price mis-specification and self-selection: downward biases

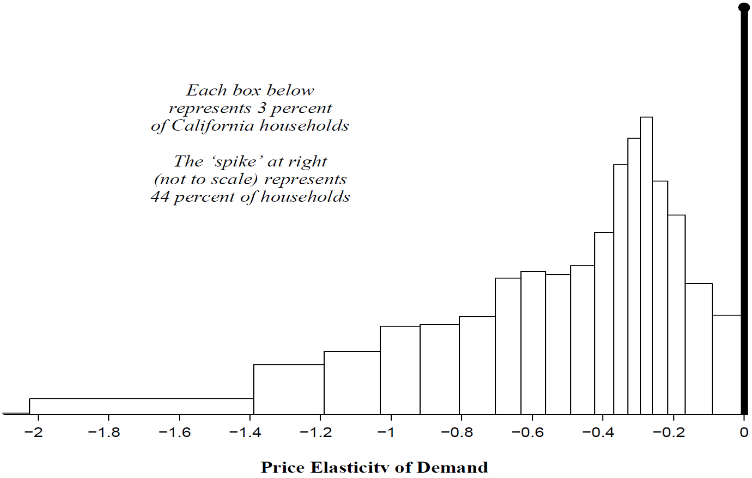
Price and Income Elasticities for CA Households

Mean Elasticities of Electricity Demand[a]	Price		Income	
	GMM Method	OLS Method	GMM Method	OLS Method
All households	−0.39	−0.28	−0.00	−0.00
Households with:				
Electric space heating	−1.02	−0.85	+0.00	+0.01
No electric space heating	−0.20	−0.11	−0.00	−0.01
Central or room air conditioning	−0.64	−0.56	+0.02	+0.02
No air conditioning	−0.20	−0.08	−0.01	−0.01
No electric space heating nor air conditioning	−0.08	+0.03	−0.01	−0.02

Heterogeneity in Price Sensitivity

- Model includes separate price and income terms for major appliances
- $\Rightarrow$ price and income elasticities vary across households
- Households with electric space heating or air conditioning exhibit a much higher electricity price elasticity
- Next figure distribution of elasticities.
- Mass point at zero with no appliances but a refrigerator (inelastic) (44% of hh)

Distribution of CA Households' Electricity Price Elasticities



Price Elasticities By Income and Electricity Consumption

- Most households will alter their electricity consumption very little in response to a price change
- A household is located in the elasticity distribution is also related to household income and other demographic characteristics
- Next table summarizes household electricity price elasticities by household income and consumption levels:
  - low income hh received subsidies tariffs
  - revenue depends on elasticities of hh with high electricity consumption
- Low income have modest high elasticities
- Elasticities are lower for hh consume high amounts of

Price Elasticities By Income and Electricity Consumption

		Price Elasticity[a]	
Quartile	Quartile Range	GMM Method	OLS Method
By household annual income level:[b]			
1st	Less than $18,000	−0.49	−0.36
2nd	$18,000 to $37,000	−0.34	−0.24
3rd	$37,000 to $60,000	−0.37	−0.27
4th	More than $60,000	−0.29	−0.19
By household annual electricity consumption:			
1st	Less than 4,450 KWh	−0.46	−0.31
2nd	4,450 to 6,580 KWh	−0.35	−0.28
3rd	6,580 to 9,700 KWh	−0.32	−0.26
4th	More than 9,700 KWh	−0.33	−0.26

Appliance Consumption Estimates

- Table provides the model's predictions about how annual electricity consumption varies by appliance
- EIA and LBL derived from a wide range of direct metering, engineering,
- General agreement between these prior studies and the model's results
- Nice validation of the model & estimates

Appliance Consumption Estimates

	Present Study		*Prior Estimates* [a]	
			Average annual use, in KWh:	
Appliance Type	Households with appliance, in percent [b]	Avg. annual electricity use, in KWh [b]	EIA (1995) [c]	LBL (1997) [c]
Elec. space heating	23.2	1,131	1,185 [b]	2,609–3,481 [d]
Central air cond.	30.3	1,270	1,283 [b]	1,306–1,446 [d]
Room air cond. [e]	13.7	619	n.a.	476 [d]
Elec. water heating	15.6	2,389	2,835	3,658
Refrigerator	99.8	1,231 [f]	1,141	1,144
Electric cooking	46.0	258	451	822
Separate freezer	16.7	582	1,013	1,026
Elec. clothes dryer	32.2	795	1,090	1,000
Clothes washer [g]	64.1	223	n.a.	100
Dishwasher [g]	48.3	241	n.a.	250
Swimming pool	5.6	2,227	n.a.	1,500 [h]
Hot tub	3.5	1,288	n.a.	2,300
Water bed heater	5.1	606	n.a.	900
Microwave	83.4	388	n.a.	132
Televisions [e]	98.3	482	n.a.	513

Household-level Consumption and Sampling Considerations

- Can compare with sales of utilities.
- No expectation RES to produce same actual mean
- RECS understates actual average consumption by slightly more than two standard errors

Electricity Consumption per Household, in KWh	Actual[a]	*Sample Data* Sample Mean	Standard Error[b]	Actual Error	*Estimated Model* Predicted Mean	Average Within-Sample Error
Pacific Gas & Elec.	6,531	5,796	258	+ 735	5,899	+103
Southern Calif. Edison	6,238	6,063	291	+ 175	5,961	−102
San Diego Gas & Elec.	5,706	4,627	514	+1079	4,775	+148
Los Angeles Wtr. & Power	5,261	5,113	454	+ 148	4,867	−246
All California	6,355	6,007	157	+ 348	6,010	+ 3

An Out-of-Sample Robustness Test

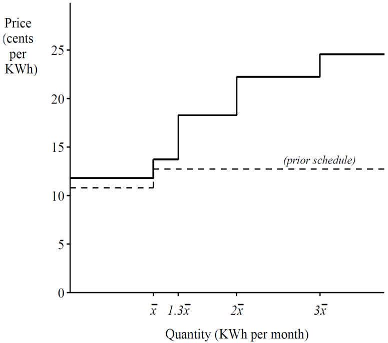
- Compare the performance of model out-of-sample with actual consumption outcomes
- In January 1998, California's three largest utilities reduced price of residential electric service by ten %
- 1998 was year of the El Nino weather disturbance

Utility Electricity Sales per Household, in KWh	Actual[a]	Predicted	Difference	Std. Error	Prob.[b]
Panel A: 1998					
Pacific Gas & Elec.	6,775	6,198	+578	252	0.02
Southern Calif. Edison	6,455	6,233	+223	280	0.43
San Diego Gas & Elec.	5,935	5,005	+930	580	0.11
Los Angeles Wtr. & Power	5,438	4,885	+554	498	0.27
Panel B: 1999					
Pacific Gas & Elec.	6,905	6,187	+718	267	0.01
Southern Calif. Edison	6,423	6,257	+136	292	0.64
San Diego Gas & Elec.	5,964	5,078	+886	647	0.17
Los Angeles Wtr. & Power	4,866	4,826	+ 40	496	0.94

- Small p-values constitute evidence against model validity

Analyzing Tariff Structure Changes-Counterfactual

- New tariff after 2001 crisis



- Household inherits from its prior (two-tier) tariff a monthly reference quantity $\bar{x}$

Analyzing Tariff Structure Changes-Counterfactual

- Three goals for new pricing:
  1. raise additional revenue for the state's utilities
  2. promote energy conservation, particularly among higher-demand consumers
  3. distributive objective: raising marginal prices more for higher levels of consumption

- No way to extrapolate its effects using descriptive (i.e., reduced-form) econometric methods

Analyzing Tariff Structure Changes-Counterfactual

- p_j is the marginal price on tier j, and $\bar{x}_j$ is the jth-tier upper boundary
- y_j denote the household's income
- Expected value of monthly household consumption:

$$E(x^*|\omega) = \sum_{j=1}^{5} P(\bar{x}_{j-1} - x_j < \varepsilon < \bar{x}_j - x_j)$$

$$[x_j + E(\varepsilon|\bar{x}_{j-1} - x_j < \varepsilon < \bar{x}_j - x_j)]$$

$$+ \sum_{j=1}^{4} P(\bar{x}_j - x_j < \varepsilon < \bar{x}_j - x_{j+1})\bar{x}_j$$

Analyzing Tariff Structure Changes-Counterfactual

- First term: contribution to expected consumption conditional on demand cross prices
- Second sum: contribution conditional on demand crossing the price schedule in one of the "gaps" between the steps

Means per household[a]	All Households	*By Income Quartile*[b] 1st	2nd	3rd	4th
Consumption (KWh/year)					
With 2 tiers (1998)	6,196	5,524	6,299	6,330	7,455
With 5 tiers	5,578	4,987	5,677	5,519	6,637
Change (%)	−10.0	−9.7	−9.9	−9.7	−11.0
Expenditures ($/year)					
With 2 tiers (1998)	718	633	734	734	873
With 5 tiers	897	770	921	925	1,120
Change (%)	24.8	21.6	25.4	25.9	28.3

Analyzing Tariff Structure Changes-Counterfactual

- Consumption 10% lower under the new five-tier tariff system
- Annual household electricity expenditures is 25 % higher
- Change in household electricity consumption between the new and old tariff systems is nearly constant across income quartiles
- Larger marginal price increases paid by households consuming higher quantities, offsets increasingly inelastic demand behavior of households with higher incomes

Introduction

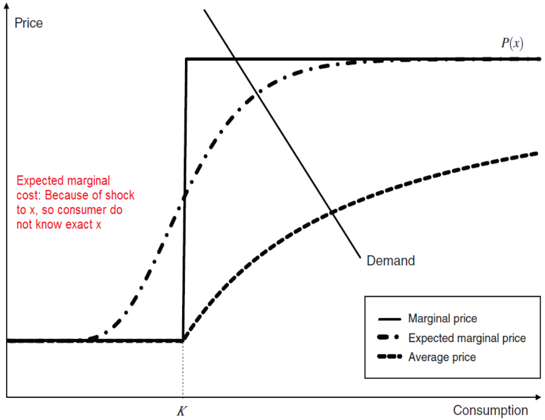
- Ito "Do consumers respond to marginal or average price? Evidence from nonlinear electricity pricing" (2014)
- Consumer responds to "marginal price", "expected marginal price", "average price",
- Identification: spatial discontinuity of two power companies.
- They changed prices independently
- Consumers respond to average price: evidence
  - if respond to marginal price $\Rightarrow$ should be bunching, but no bunching of consumers at kink points of nonlinear price schedules.
  - encompassing test: marginal & expected marginal no effect on consumption when control for average price.

Policy Implication

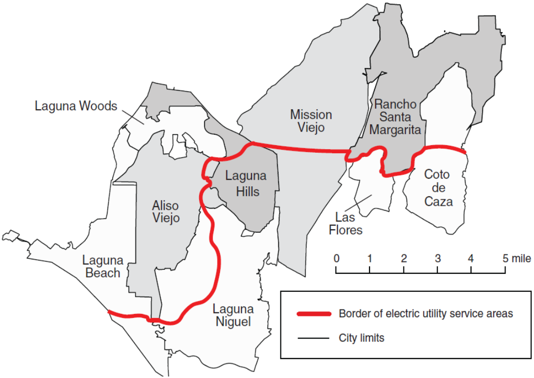
- Nonlinear pricing is not working:
  - goal: higher marginal prices for excessive consumption, so conservation
  - if respond to average price: nonlinearity may increase consumption
- Ineffective cap-trade policy
  - Govt. distribute free allowance to electric companies
  - They must on a flat base decrease the payment of all bills to keep up marginal prices
  - But if respond to average price, this policy may increase cons.
- Consumer inattention to complex pricing

Consumer Perceived Price in 3 Models

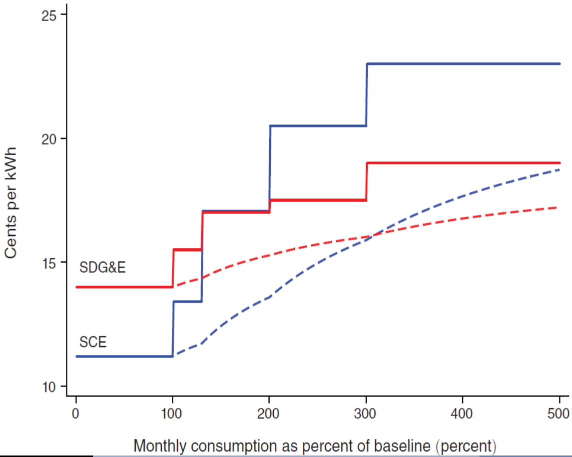
Panel A. Three theoretical predictions



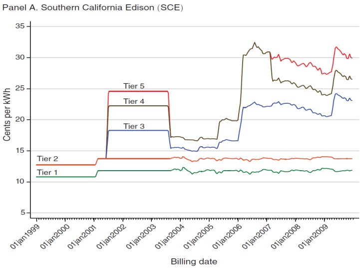
Predetermined power supply by address

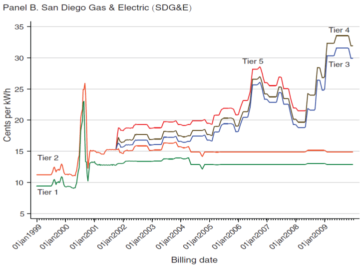


Nonlinear Electricity Pricing and Price Variation-An Example

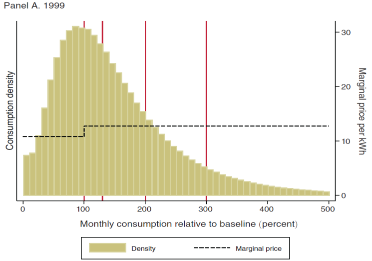


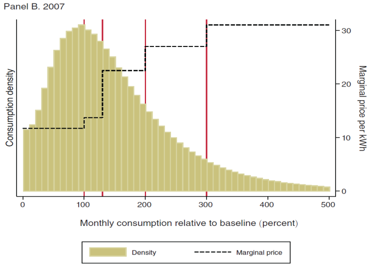
Real Time and Cross Sectional Price Variation





No Bunching-Even with Steep Steps





- Bunching regression: zero elasticity

Encompassing Tests of Alternative Prices

- Respond consumption to marginal or average price:

$$\Delta ln(x_{it}) = \beta_1 \Delta ln(MP_{it}) + \beta_2 \Delta ln(AP_{it}) + \gamma_{ct} + \eta_{it}$$

- Identification: price function of consumption so corr. with error
- IV: policy induced price change $\Delta ln(MP_{it}^{PI}) = ln(MP_t(\tilde{x}_{it})) - ln(MP_{t0}(\tilde{x}_{it}))$
- Condition $\tilde{x}_{it}$ uncorrelated with $\eta_{it} = \varepsilon_{it} - \varepsilon_{it0}$. Best suggestion midyear consumption as $\tilde{x}_{it} = x_{it_m}$
- Combine this idea with discontinuity in the city. Add flexible variable $f_t(x_{it_m})$. Since, we have two pricing regime we can identify β using this flexible function.

Main Regression

- With AV, MP not change the effect of average price
- Effect of MP becomes statistically insignificant from zero

	(1)	(2)	(3)	(4)	(5)	(6)
$\Delta \ln(\textit{marginal price}_t)$	−0.034 (0.004)		0.002 (0.011)			
$\Delta \ln(\textit{average price}_t)$		−0.051 (0.005)	−0.054 (0.015)			
$\Delta \ln(\textit{marginal price}_{t-1})$				−0.050 (0.004)		0.006 (0.011)
$\Delta \ln(\textit{average price}_{t-1})$					−0.074 (0.005)	−0.082 (0.015)

- Find expected price by logit regression on grid of consumption times their MP/AP

	(1)	(2)	(3)	(4)
$\Delta \ln(\textit{expected marginal price}_t)$	−0.036 (0.004)	0.004 (0.012)		
$\Delta \ln(\textit{average price}_t)$		−0.056 (0.015)		
$\Delta \ln(\textit{expected marginal price}_{t-1})$			−0.053 (0.004)	0.009 (0.012)
$\Delta \ln(\textit{average price}_{t-1})$				−0.086 (0.015)

Introduction

- Jessoe, & Rapson "Knowledge is (less) power: Experimental evidence from residential energy use" AER (2014)
- Prior studies: low price elasticity
- May be due to coarse billing and less information
- RCT:
  - all treatment households to exogenous price changes (200%-600% increase) (all informed)
  - a random subset of these exposed to real-time feedback on quantity of electricity consumed via an in-home display (IHD).
- Results:increases price elasticity of demand by 3 std.
  - only price change:reduce cons by 0-7%
  - Price +IHD: reduce cons by 8-22%

Research Design

- Three groups: control, price ("price-only"), and price-plus-information ("price + IHD")
- Price signal and variation: "DA": day-ahead \$0.5 inc (high temperature expected), "TM": thirty minutes before \$1.25 inc (grid instability)

Event date	Desc	Type	Start hour	High temp	Mean temp	Humidity
07/21/11	4 hr \$0.50	DA	12	89	82	75
07/22/11	4 hr \$1.25	TM	12	103	90	61
08/04/11	2 hr \$0.50	DA	15	80	74	68
08/10/11	2 hr \$1.25	TM	16	88	80	63
08/17/11	2 hr \$1.25	TM	16	86	75	64
08/26/11	4 hr \$0.50	DA	12	84	78	69

- Notification by e-mail, phone call, text message, depending on their stated preference.
- Three groups are balanced based on pre-trial survey of characteristics
-

Simple comparison of raw unbalanced panel

		Mean kWh during events			Difference in mean kWh wrt control	
Event type	Variable	Control	Price	Price + IHD	Price	Price + IHD
Sample: Unbalanced panel	assigned to a treatment for which we observe usage data for "at least one pricing event"					
DA	Mean	1.65	1.59	1.35	−0.06	−0.30*
	SD	(1.51)	(1.25)	(1.22)		
	Obs	207	130	100		
TM	Mean	2.07	1.99	1.79	−0.07	−0.28
	SD	(1.77)	(1.54)	(1.42)		
	Obs	186	128	87		
Sample: Balanced panel	assigned to a treatment for which we observe usage data for "all pricing events,"					
DA	Mean	1.79	1.67	1.54	−0.13	−0.25
	SD	(1.56)	(1.13)	(1.24)		
	Obs	172	90	77		
TM	Mean	2.17	2.17	1.92	0.00	−0.25
	SD	(1.79)	(1.39)	(1.44)		
	Obs	172	90	77		

Results: Information and Price Elasticity

- Simple difference-in-differences model

$$q_{it} = \sum_{g \in \{P, P+I\}} \beta_g D_{it}^g + \gamma_g + \delta_e + \mu_{it}$$

- q_{it} natural log of energy usage in 15 minute interval t
- Treatment dummy D_{it}^g in group g+pricing event occur
- Pricing event indicatorδ_e
- Separate treatment group dummies μ_{it}
- Additional controls: hour-by-calendar-date dummies, household fixed effects and a combination of two.
- Three panels:
  - ITT: OLS of usage on initial assignment to treatment
  - ToT: 2SLS where initial treatment assignment is used as an instrument for receipt of treatment
- β: average percentage change in electricity usage from assignment to treatment during pricing events

Treatment Effects (Unbalanced Panel)

Event type:	All (1)	All (2)	All (3)	All (4)	Day ahead (DA) (5)	30min (TM) (6)
Panel A. ITT unbalanced panel						
Price-only	−0.031	−0.054	−0.027	−0.038	−0.071*	0.006
	(0.036)	(0.036)	(0.036)	(0.036)	(0.042)	(0.044)
Price + IHD	−0.116**	−0.137***	−0.123***	−0.137***	−0.171***	−0.084
	(0.048)	(0.048)	(0.047)	(0.046)	(0.051)	(0.057)
Prob($P = P + I$)	0.096*	0.098*	0.051*	0.044**	0.066*	0.130
R^2	0.001	0.054	0.536	0.583	0.583	0.583
Panel B. ToT unbalanced panel						
Price-only	−0.032	−0.056	−0.028	−0.040	−0.074*	0.007
	(0.037)	(0.037)	(0.037)	(0.037)	(0.044)	(0.046)
Price + IHD	−0.143**	−0.170***	−0.153***	−0.170***	−0.217***	−0.100
	(0.058)	(0.058)	(0.057)	(0.057)	(0.064)	(0.067)
Prob($P = P + I$)	0.061*	0.052*	0.030**	0.023**	0.025**	0.115
R^2	0.001	0.054	0.536	0.583	0.583	0.583
HH FEs	No	No	Yes	Yes	Yes	Yes
Hour-by-day FEs	No	Yes	No	Yes	Yes	Yes
Number of events	6	6	6	6	3	3
Number of HHs	437	437	437	437	437	401