A Structural Approach to Dynamic Energy Pricing and Consumer Welfare

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Motivation

Dynamic Pricing

- Increasing availability in US over past 5 years
- Well studied: many RCTs estimate average treatment response
- Few studies of welfare effects

Identification Problems:

- Low price variation during off-peak hours
  - Hausman, Kinnucan, McFadden (1979) - A Two-Level Electricity Demand Model
- Average Welfare with unobserved heterogeneity
  - Hausman and Newey (2016) - Individual Heterogeneity and Average Welfare

Motivation

Contribution

- High Frequency Household consumption data from RCT
- Methodology for causal analysis using ML to generate counterfactuals, matches
- Policy analysis of specific dynamic rate that was adopted by Utility

Findings

- High variation in price elasticity of demand throughout day
- In this experiment, consumer welfare gain during off-peak hours exceeds consumer welfare loss for all but the highest peak prices

Experiment

Rate Structure

Dynamic Price - Treated Group

- Price per KW during off-peak hours is constant: $0.045
  - Off-Peak Hours: 12 a.m. - 2 p.m., 7 p.m. - 12 a.m.
- Price per KW during peak hours for all treated households is chosen by Utility each day:
  $0.045, $0.113, $0.23, $0.46
  - Peak Hours: 2 - 7 p.m.

Standard Block Rate - Control Group

- Constant price per KW each day
  - Price per KW: $0.083 for the first 1400 KW used in a month
  - $0.096 per KW for additional usage

Experiment

Consumption Data

- Consumption observed in 15 minute increments for 2010, 2011
- Household Behavior observed in 2010 was before households enrolled in Experiment
  - Control Households experience no change in technology or price
  - Treated Households exposed to new technology and new price
  - Treated Households' behavior observed under both policies

	2010		2011
Control	Standard Rate	$\rightarrow$	Standard Rate
Treatment	Standard Rate	$\rightarrow$	Dynamic Rate

2,146,464 observations of hourly household consumption

Identification Strategy

Difference in Difference

- Ideally we could regress quantity on observed price, controlling for weather to account for endogenous price setting decision
- Identification problem: only one price observed during off-peak hours ($0.045/KWH)
- Can simulate behavior of treated households in 2011 using pretreatment data from 2010

$$\left[\begin{array}{c|c} W_0^{10} : \text{2010 Control Households} & W_0^{11} : \text{2011 Control Households} \\ \hline Y_0^{10} : \text{2011 Treated Households} & Y_1^{11} : \text{2011 Treated Households} \end{array}\right]$$

Identification strategy follows from simulating $\widehat{Y_0^{11}}$

Counterfactuals - Lasso Prediction

see Burlig, Knittlel, Rapson, Reguant, and Wolfram 2018

1. Model consumption in 2010 as a function of observed variables in 2010
2. Use penalized regression (Lasso, Ridge, Elastic Net) to select model with best fit for 2010 data
3. Predict consumption in 2011 by using observations of variables in 2011 in function with parameters chosen in (2)

Variable Pool

- Temperature
- Humidity
- Dewpoint
- Previous Day Cooling Degrees
- Average consumption among similar households
- Month and Day-of-week fixed effects

Counterfactuals - Vertical Regression + Lasso

see Athey, Bayati, Doudchenko, Imbens, and Khosravi 2018

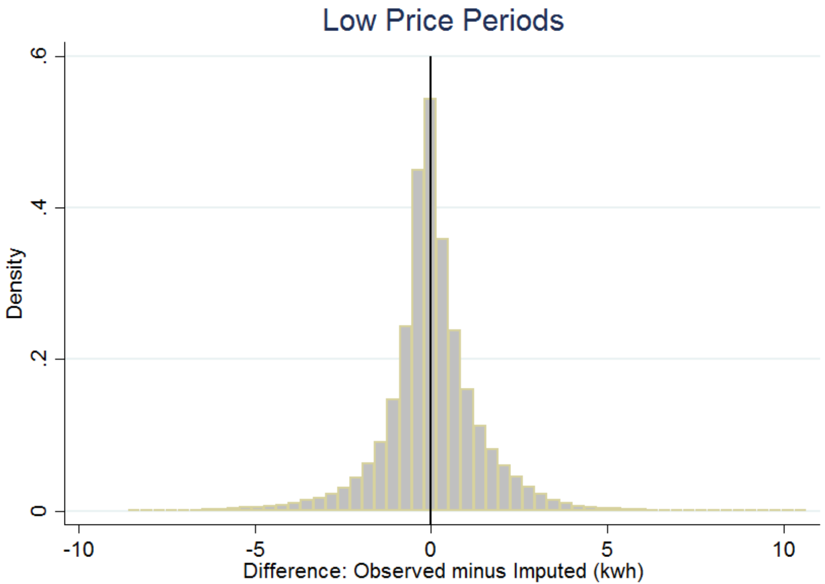
1. Consider J control units and $K = 2$ treated units Y_{N-1}, Y_N:

$$\left[\begin{array}{cc|cc} \text{Pre Treatment} & & \text{Post Treatment} & \\ Y_{1,1} & Y_{1,2} & Y_{1,3} & Y_{1,4} \\ \ldots & \ldots & \ldots & \ldots \\ Y_{J,1} & Y_{J,2} & Y_{J,3} & Y_{J,4} \\ \hline Y_{N-1,1} & Y_{N-1,2} & ? & ? \\ Y_{N,1} & Y_{N,2} & ? & ? \end{array}\right]$$

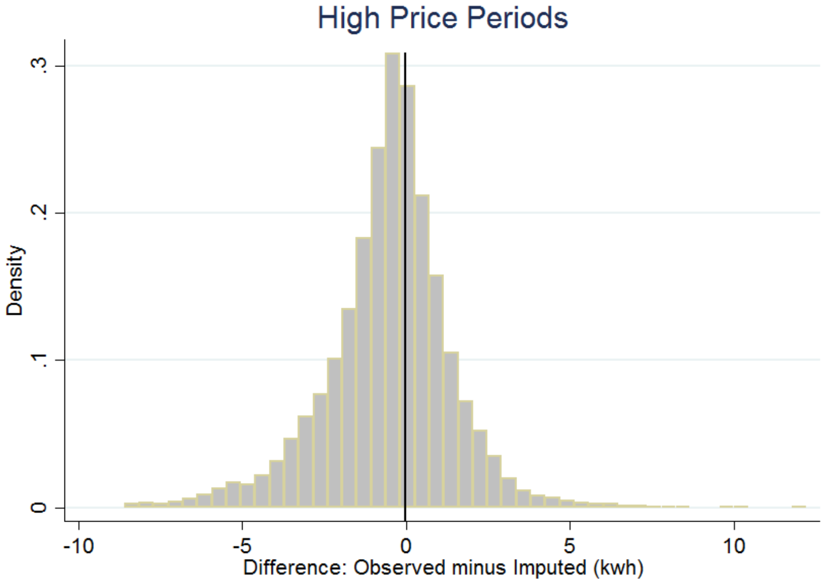
2. Use shrinkage estimator to select from among many possible control households J as covariates
3. Impute counterfactual untreated behavior behavior of Y_{N-1}, Y_N during treated periods:

$$\hat{Y_{N,t}} = \hat{\beta}_0 + \sum_{i=1}^{N} \hat{\beta}_i Y_{i,t}$$

Predictions



Predictions



Elasticity Estimation

Constant Elasticity Specification

$$ln(Q_{i,h}^{2011}) = ln(a) + \gamma ln(p_h) + \sum_{j=-1}^{j=+1} \delta_j ln(T_j) + \varepsilon_{i,h} \quad (1)$$

- Constant Elasticity specification allows one-step estimation of price elasticity conditional on temperature
- Temperature Control accounts for omitted variable bias stemming from correlation between high price and high consumption on hottest days of summer.

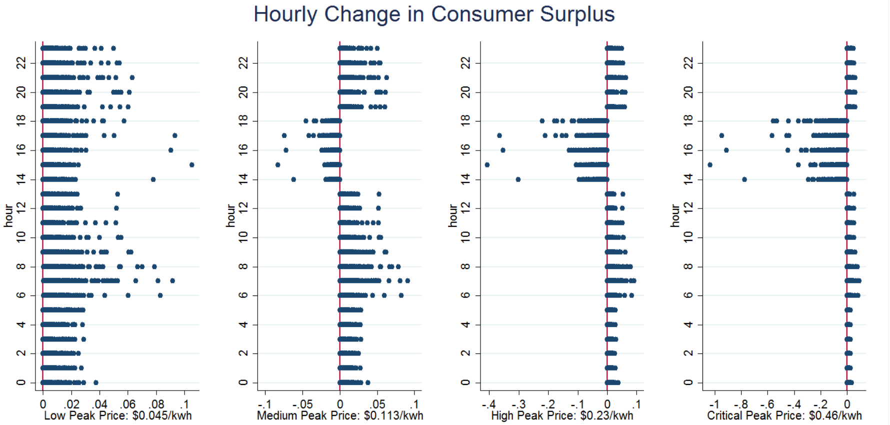
Computing Consumer Surplus

Analytic Solution

$$\Delta CS_h = a * T_{h-1}^{\hat{\delta}_{1,h}} * T_h^{\hat{\delta}_{2,h}} * T_{h+1}^{\hat{\delta}_{3,h}} * \frac{[p_2^{1+\hat{\gamma}_h} - p_1^{1+\hat{\gamma}_h}]}{1+\hat{\gamma}_h} \quad (2)$$

- Consumer Surplus increases in off-peak hours where price falls from control rate \$0.083 to off-peak price \$0.045
- Consumer Surplus decreases in on-peak hours where price rises to either \$0.113, \$0.23, or \$0.46

Estimation: Consumer Surplus



Estimation: Consumer Surplus

Average Household Effects

- Off-peak price more than compensates for consumer surplus loss on days with medium and high peak prices
- Critical price days are net reductions in consumer surplus
- In 2011, with 23 low, 30 medium, 22 high, and 12 critical price days, average change in consumer surplus is $4.63 per household

	Daily Change in Consumer Surplus	Peak Hours Only	Off-Peak Hours Only	Average Ratio Peak:Off-Peak
Low Peak Price	$0.15	0.0269	0.1234	-
Medium Peak Price	$0.10	-0.0218	0.1239	-0.1759
High Peak Price	$0.01	-0.1106	0.1240	-0.9064
Critical Peak Price	-$0.17	-0.2964	0.1241	-2.4844

Conclusions

Methodology

- ML forecasts trained on pretreatment data forecast counterfactual (untreated) behavior
- Counterfactual predictions identify household specific price elasticity of demand
- Identification strategy evades problems with unobserved individual heterogeneity

Policy

- Household consumer surplus effects are small but positive
- Utility could have offered a less drastic discount without reducing consumer welfare