It's About Time: Transitioning to Time-of-Use Pricing and Consumer Demand for Electricity

Greg Kirwin

May 2025

Motivation

- Aggregate electricity consumption fluctuates throughout the day

Motivation

- Aggregate electricity consumption fluctuates throughout the day
- Costs and emissions are higher during peak demand

Motivation

- Aggregate electricity consumption fluctuates throughout the day
- Costs and emissions are higher during peak demand
- California Public Utilities Commission (CPUC) wanted to promote energy conservation by getting consumers to shift the timing of their energy use

Motivation

- Aggregate electricity consumption fluctuates throughout the day
- Costs and emissions are higher during peak demand
- California Public Utilities Commission (CPUC) wanted to promote energy conservation by getting consumers to shift the timing of their energy use
- Problem: Under flat and block pricing, there is no incentive to adjust the timing of usage

Policy Setting

CPUC mandated the rollout of "Time-of-Use" (TOU) pricing across California's major public utilities

- Consumers were allowed to opt out of the program with no penalty

Policy Setting

CPUC mandated the rollout of "Time-of-Use" (TOU) pricing across California's major public utilities

- Consumers were allowed to opt out of the program with no penalty
  - Opting out removes the incentive to change consumption

Policy Setting

CPUC mandated the rollout of "Time-of-Use" (TOU) pricing across California's major public utilities

- Consumers were allowed to opt out of the program with no penalty
  - Opting out removes the incentive to change consumption
- Consumers that switch may face a salience issue

Policy Setting

CPUC mandated the rollout of "Time-of-Use" (TOU) pricing across California's major public utilities

- Consumers were allowed to opt out of the program with no penalty
  - Opting out removes the incentive to change consumption
- Consumers that switch may face a salience issue
  - Habit adjustment may be slow

Questions

1. Why did consumers opt out of the change in rate structure?

Questions

1. Why did consumers opt out of the change in rate structure?
2. How do residential electricity customers respond to changes in plan structure when automatically enrolled?

Questions

1. Why did consumers opt out of the change in rate structure?
2. How do residential electricity customers respond to changes in plan structure when automatically enrolled?
3. What are the implications for future rate change programs?

Preview of Results

I find that:

1. Opt-out is higher when...
   - Prices would have increased more dramatically
   - Electricity usage is more volatile

Preview of Results

I find that:

1. Opt-out is higher when...
   - Prices would have increased more dramatically
   - Electricity usage is more volatile
2. TOU customers adjusted slowly
   - Seasonal price variation affected the extent of adjustment
   - Summer kWh $\downarrow 1.2\%$ after more than 12 months
   - Summer peak kWh $\downarrow 3.7\%$ in first 12 months
   - Winter consumption unchanged or increased

Preview of Results

I find that:

1. Opt-out is higher when...
   - Prices would have increased more dramatically
   - Electricity usage is more volatile
2. TOU customers adjusted slowly
   - Seasonal price variation affected the extent of adjustment
   - Summer kWh $\downarrow 1.2\%$ after more than 12 months
   - Summer peak kWh $\downarrow 3.7\%$ in first 12 months
   - Winter consumption unchanged or increased
3. Disallowing opt-out would ensure that consumers with the highest peak demand adjust their behavior

Relevant Literature

- Dynamic pricing in electricity: Boiteux (1947), Houthhaker (1951), Steiner (1957), Ham et al. (1997), Herter (2007), Train and Mehrez (1994), Wolak (2010), Joskow and Wolfram (2012), Harding and Sexton (2017), Hinchberger et. al (2024), Faruqui and Tang (2023), **Bernard et. al (2024)**
  - Contribution: Consumer response to dynamic pricing within billing cycles and across seasons

- Program default behavior: Carroll et al. (2009), Bernheim et al. (2015), Blumenstock et al. (2018), **Fowlie et. al (2021)**, Ito et. al (2023), **Cahana et. al (2023)**, **Enrich et. al (2024)**
  - Contribution: Consumer choice to opt out of a change in price structure

Roadmap

1. Walkthrough of electric utilities and program implementation

Roadmap

1. Walkthrough of electric utilities and program implementation
2. Estimate the probability of switching conditional on observable factors

Roadmap

1. Walkthrough of electric utilities and program implementation
2. Estimate the probability of switching conditional on observable factors
3. Estimate the causal effect of the switch to TOU on consumption

Roadmap

1. Walkthrough of electric utilities and program implementation
2. Estimate the probability of switching conditional on observable factors
3. Estimate the causal effect of the switch to TOU on consumption
4. Predict a counterfactual of load under forced TOU adoption

Background

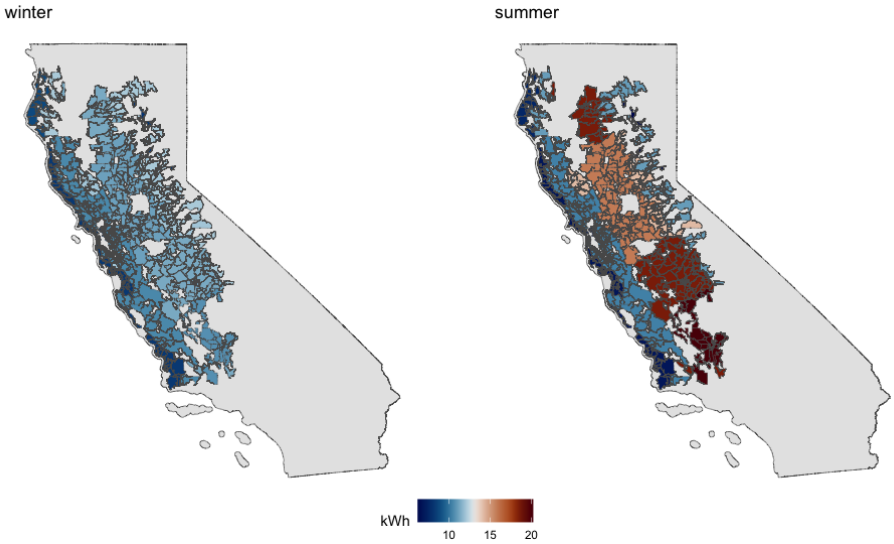
Electric Utilities: Plan Types

- Flat or "block pricing" plans are most common in the US
  - Flat: $Cost = \$/kWh \times kWh$
  - Block: MC increases at usage thresholds
- Dynamic Pricing: Price changes depending on demand
- With TOU, price increases during high-demand hours set by the utility (usually the evening)

Electric Utilities: Geographic Differences

- Usage tiers are set using local climate conditions, organized into "climate zones"
- "Baseline" threshold is the zone's median daily usage
- Tiers change in winter (October-May) and summer (June-September)

Electric Utilities: Baselines by Climate Zone and Season



Electric Utilities: TOU Rollout

- TOU implemented via opt-out
  - $\sim$ 40% opt out across all zones
  - The rest were transitioned
  - Exempt: CARE/FERA, solar, alternative plans
- Rollout was done in 9 "waves" of counties
- Rollout ran from April 2021 through through April 2022

Covid

Electric Utilities: TOU Rollout

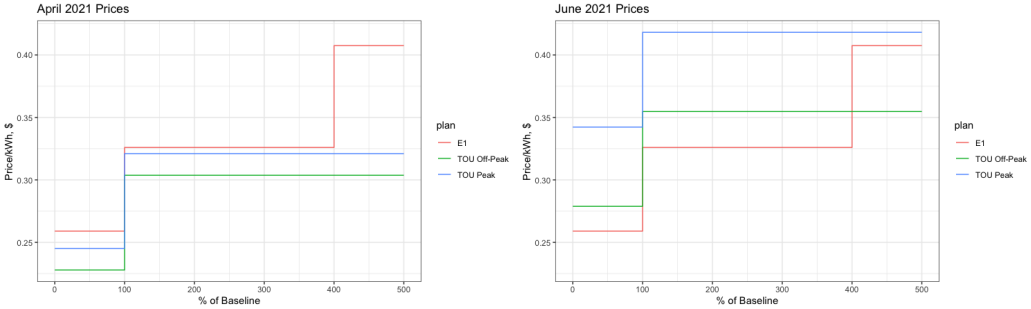
- Consumers were notified 4 months before rollout
- Nonresponse led to automatic opt-in
- Could compare previous bills under the block and TOU prices
- "Bill protection" for the first 12 months after transition
  - Rebate account if TOU bill is higher than previous plan
  - Insures against bill shock from the switch

Electric Utilities: Prices

- TOU plan prices are...
  - dynamic across hours
  - seasonal
  - tiered
- Consumers face lower prices on TOU in winter (October—May)...
  - but higher prices in the summer (June—September)

Prices By Usage

Discount in winter, cost increase in summer:



Price Over Time

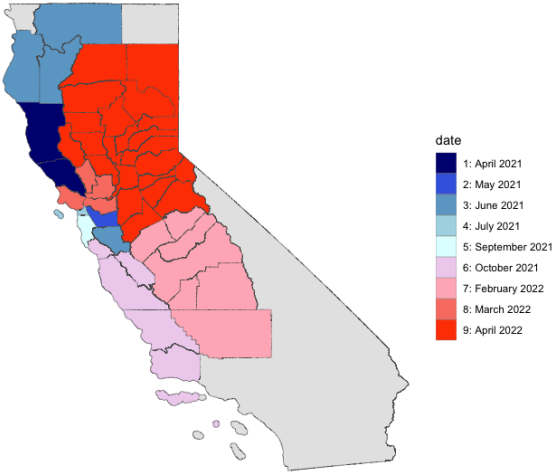
Data Sample

Primary Dataset from Pacific Gas & Electric

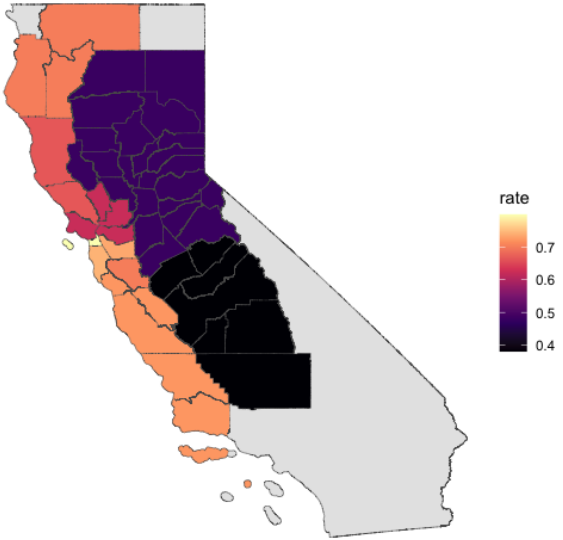
- 75,000 single-family households
- Zip code-level anonymization
- Could not switch homes during sample period
- Two main sets of files
  - Hourly meter data from 2018-2021
  - Monthly bills 2018-2022
- Includes: rate, hourly usage, home solar, income assistance indicators, climate zone, total bill amount
- Missing: addresses, household characteristics, demographics

Trimming

Program Rollout



Percent Switching to TOU



Pre-Rollout Summary Statistics

Opt-outs ("stayers")...

- Consume more on each bill
- Consume more during peak
- Peak is a higher percentage of their usage
- Their bills are higher

Full table

	Switch		Stay	
	Mean	**SD**	**Mean**	**SD**
kWh	522.91	346.38	567.12	368.22
Peak kWh	146.26	109.27	165.92	123.53
$	139.65	107.17	145.92	106.18

Empirical Framework

Framework: How do consumers decide to opt out?

Fowlie et al. (2021): Switching costs and inattentiveness for consumers' consumption habits

- Customers are presented with the choice to opt out via their account
- Compare cost of prior usage under both plans
- Can opt out to suit their own interests, potential for advantageous selection
- Some consumers may not be aware of this option due to inattentiveness
  - Only opt-out is observed directly
  - Observe both opting out and switching regardless of cost differences

Cost Difference of Switching

Cost difference of switching:

- What customer *would have paid* on TOU in the 12 months before switch
- Opt-outs have higher losses in summer, average net loss over the year
- Shown: *Block* − *TOU* cost. Excludes the last 3 waves, May and September.

	Summer		Winter		Pre-Rollout Total	
	Mean	**Median**	**Mean**	**Median**	**Mean**	**Median**
Switch	-19.59	-16.33	9.19	8.69	4.66	10.18
Stay	-24.33	-19.77	10.08	8.89	-3.74	5.69

Cost Breakdown by Month | Cost Bin Scatter

Selection

Why Opt Out?

Possible reasons to opt out:

- The customer wants to avoid paying a premium on future peak-hour usage

Why Opt Out?

Possible reasons to opt out:

- The customer wants to avoid paying a premium on future peak-hour usage
- The customer saw (a) negative-value month(s) in the rate cost comparison

Why Opt Out?

Possible reasons to opt out:

- The customer wants to avoid paying a premium on future peak-hour usage
- The customer saw (a) negative-value month(s) in the rate cost comparison
- The customer is very elastic to changes in cost between bills

Why Opt Out?

Possible reasons to opt out:

- The customer wants to avoid paying a premium on future peak-hour usage
- The customer saw (a) negative-value month(s) in the rate cost comparison
- The customer is very elastic to changes in cost between bills
- The customer has more uncertainty about their usage and is concerned about their bill increasing

Possible Sources of Selection

Run probits to predict switching:

$$Y_{ijk} = X\beta + \gamma_j + \gamma_k + \epsilon_{ijk}$$

- Household i in wave j, climate zone k
- $X\beta$ are predictors of switching behavior
- $Y_{ijk} = \mathbf{1}\{\text{Switch to TOU}\}$

1. Consumer uncertainty over future consumption Output 1 Output 2

Possible Sources of Selection

Run probits to predict switching:

$$Y_{ijk} = X\beta + \gamma_j + \gamma_k + \epsilon_{ijk}$$

- Household i in wave j, climate zone k
- $X\beta$ are predictors of switching behavior
- $Y_{ijk} = \mathbf{1}\{\text{Switch to TOU}\}$

1. Consumer uncertainty over future consumption Output 1 Output 2
2. Monthly variation in bills Output

Possible Sources of Selection

Run probits to predict switching:

$$Y_{ijk} = X\beta + \gamma_j + \gamma_k + \epsilon_{ijk}$$

- Household i in wave j, climate zone k
- $X\beta$ are predictors of switching behavior
- $Y_{ijk} = \mathbf{1}\{\text{Switch to TOU}\}$

1. Consumer uncertainty over future consumption Output 1 Output 2
2. Monthly variation in bills Output
3. Expected costs of TOU versus block pricing Output

Selected Variables

- Cost difference, winter and summer
- Pre-Covid work and off-work hours
- Average bill deviation
- Average summer max temperature
- Mean peak usage, weekday and weekend
- Average total kWh

Covid Summary Statistics

Probit Results

A 1 s.d. increase in...

- Summer cost difference decreases switch probability by 8%
- Weekday peak kWh decreases switch probability by 18%
- Weekend peak kWh increases switch probability by 7%
- Monthly bill variance decreases switch probability by 17%

Treatment Effects

Identification

Want to identify:

- Treatment effect due to seasonal price variation
- Treatment effect of time-dependent prices

Identification strategy relies on parallel trends between opt-out and switching customers:

- Exploit variation within waves
- Consumers are separated into treated and control
  - Opt-outs are control; stay on original plan
  - Switchers are treated via the new plan
- Little evidence of an anticipation effect
- Callaway-Sant'Anna (2021) not feasible due to limited post-rollout data

Treatment Effects: TWFE

Use two-way fixed effects (TWFE) to estimate the treatment effect from switching to TOU Model:

$$Y_{it} = \beta_0 + \beta_1 switched_i \times post_{jt} + \gamma_i + \gamma_{jt} + X_{it} + \epsilon_{it}$$

Treatment Effects: TWFE

Use two-way fixed effects (TWFE) to estimate the treatment effect from switching to TOU
Model:

$$Y_{it} = \beta_0 + \beta_1 switched_i \times post_{jt} + \gamma_i + \gamma_{jt} + X_{it} + \epsilon_{it}$$

- Y_{it}: outcome for household i in period t
- *switched* an indicator that i switches plans
- *post* an indicator that wave j has transitioned
- Fixed effects: household i; wave j $\times$ month $\times$ year
- Note: omits 2020 and Jan-Mar 2021

TWFE Estimates

	log(Total kWh)	log(Bill $)
Post x Switch	-0.003	-0.908
	(0.003)	(0.004)
R2	0.847	0.846
N	547,853	547,855
RMSE	0.214	0.242
Mean of Y	6.033	4.716

Peak

TWFE: Refinements

The base TWFE model has issues due to the design of the program:

1. Prices move in opposite directions from the pre-transition period during summer and winter
2. Consumers have access to "bill protection" for the first 12 months of the transition

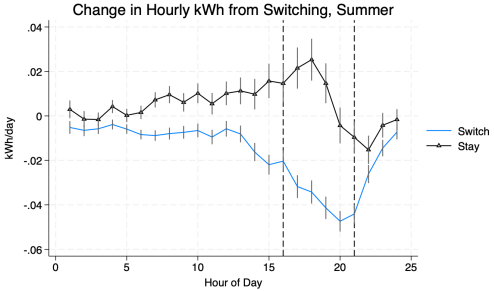
Seasonal

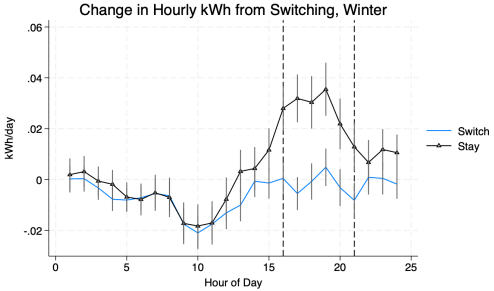
TWFE With Seasons and Periods

	log(Total kWh)	log(Bill $)
Post x Switch, Summer <= 12 Months	-0.037	0.055
	(0.004)	(0.005)
Post x Switch, Summer >12 Months	-0.048	0.027
	(0.006)	(0.006)
Post x Switch, Winter <= 12 Months	0.019	-0.044
	(0.004)	(0.004)
Post x Switch, Winter >12 Months	0.022	-0.039
	(0.005)	(0.005)
R2	0.848	0.847
N	547,853	547,855
RMSE	0.214	0.242
Mean of Y	6.033	4.716

By month

Changes By Hour





Hourly TWFE

Matching Estimation

- Matching Difference-in-differences groups consumers with similar observable attributes
- I use propensity score matching (PSM) with the selected probit variables
- Advantage over TWFE is in accounting for heterogeneity in pre-treatment demand

Treatment Effects: Matching Estimator

Estimated equation:

$$ATE = \sum_{i=1}^{N} \frac{1}{N}[\Delta Y_i - \sum_{j \in nbh(i)} \frac{1}{|nbh(i)|} Y_j]$$

where:

- ΔY_i is the mean difference of household i's consumption, pre- and post-rollout
- $nbh(i)$ is the number of neighbors j matched to i based on their propensity score
- Y_j the change in outcome for treated units
- N the number of treated units

Matching with Long/Short Difference

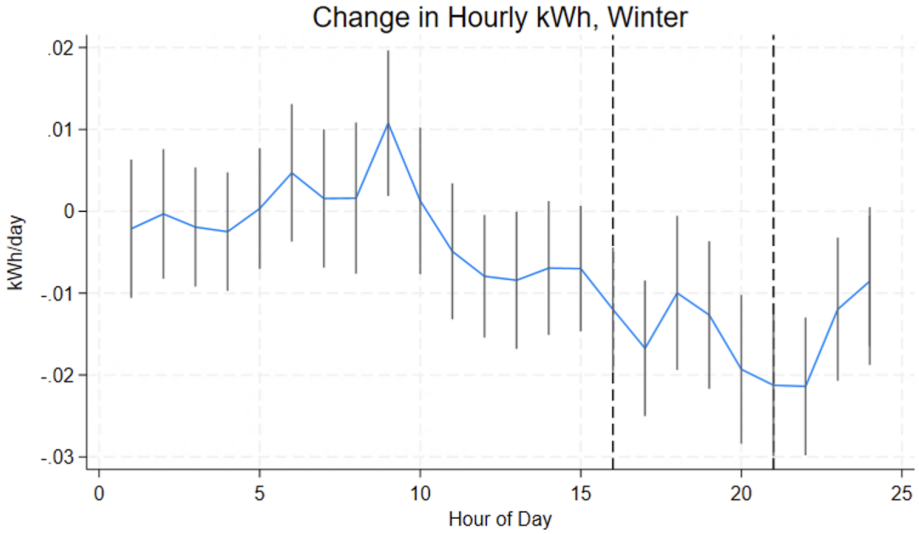
Using the first 5 waves only:

	KWH				Billing			
	Summer		Winter		Summer		Winter	
	Short	Long	Short	Long	Short	Long	Short	Long
ATE	-1.656	-5.501	0.503	1.225	16.882	14.706	-8.080	-8.396
	(1.610)	(2.159)	(1.358)	(2.409)	(0.627)	(0.910)	(0.529)	(0.967)
Neighbors	25	25	25	25	25	25	25	25
N	8,508	8,508	10,309	10,309	8,508	8,508	10,309	10,309
Mean of ΔY	-9.76	8.09	-40.27	34.07	9.055	64.394	6.146	55.107
Pre-Rollout Mean	451.98	451.98	439.83	439.83	111.39	111.39	110.28	110.28

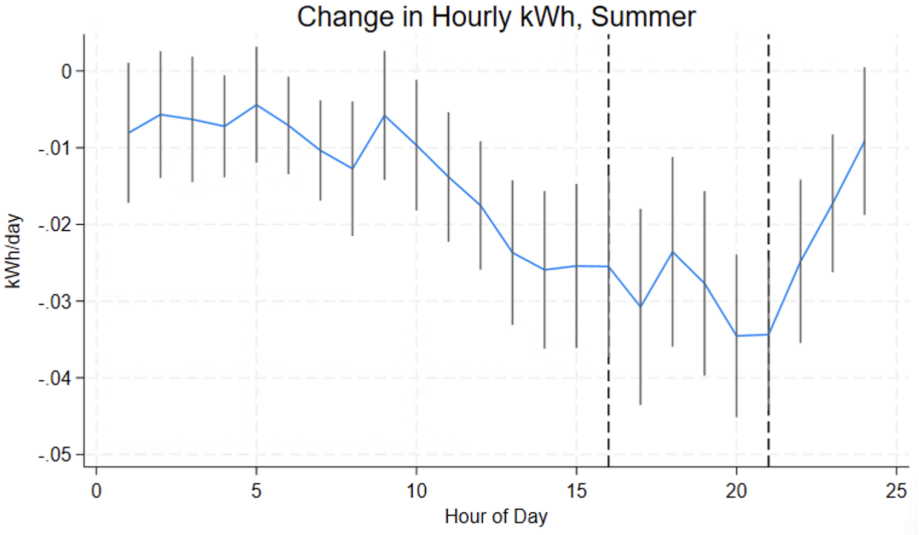
Matching with Peak Consumption

	Peak		Peak %	
	Summer Short	**Winter Short**	**Summer Short**	**Winter Short**
ATE	-5.050	-1.701	-0.008	-0.005
	(0.800)	(0.559)	(0.001)	(0.001)
Neighbors	25	25	25	25
N	8,508	10,309	8,508	10,309
Mean of ΔY	1.28	-12.763	-0.002	-0.001
Pre-Rollout Mean	131.43	120.75	0.281	0.275

Hourly Matching, Winter



Hourly Matching, Summer



Counterfactuals

Post-Estimation: Policy Changes

I consider two policy alternatives using hourly-level data from 2021:

1. Disallow opt-out
2. Disallow TOU transition altogether

I use the estimated ATE for both monthly bills and hourly demand to estimate changes under these two policies:

- Apply estimated ATE to opt-outs in **1**
- Remove estimated ATE from switches in **2**

Monthly Changes

Counterfactual 1: No Opt-Out

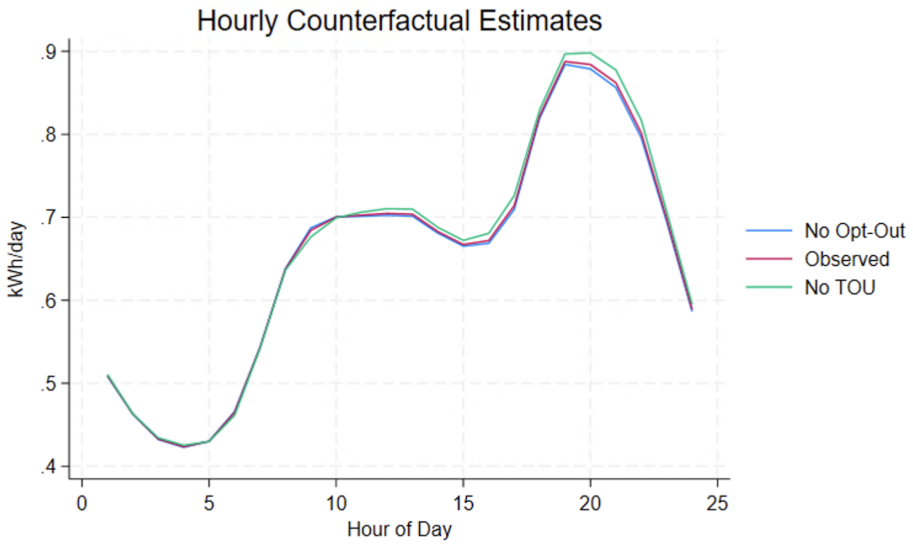
	Summer		Winter	
	Mean	**Median**	**Mean**	**Median**
Total	-0.26	-0.29	-0.45	-0.49
Peak	-1.23	0.84	0.23	0.22

Counterfactual 2: No TOU

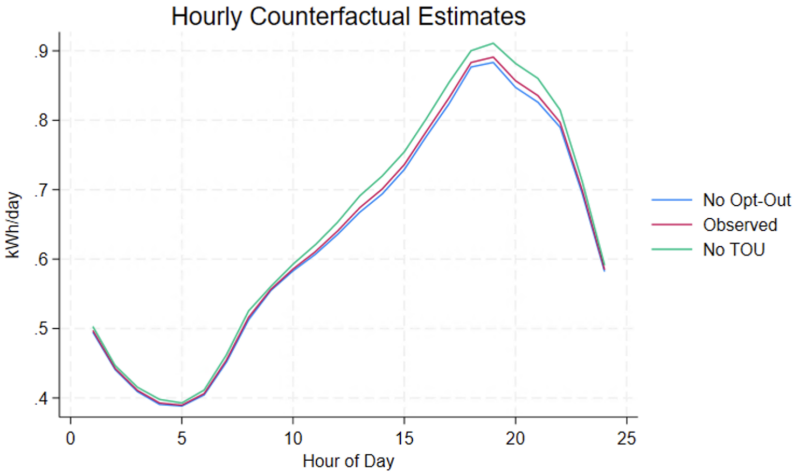
	Summer		Winter	
	Mean	**Median**	**Mean**	**Median**
Total	0.64	0.47	-1.15	-0.92
Peak	2.88	2.42	0.62	0.53

Hourly

Hourly Changes, Winter



Hourly Changes, Summer



Concluding Remarks

Wrapping Up

What I've done:

- Use a large, varied dataset of residential electricity under a drastic rate change program
- Assess whether this program was subject to advantageous selection
- Estimate the ATE for households that were automatically opted into the program, finding that they did not respond as much as we might expect

Policy Takeaways

- Removing opt-out would ensure that customers are incentivized to change their habits in the summer
- Winter season pricing removes the incentive to adjust to the peak design
- "Bill protection" muted initial behavioral adjustments

Thank you!

I appreciate your comments, questions, and feedback!

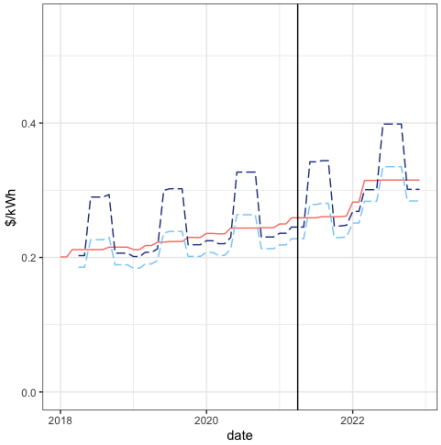
Supplemental Slides

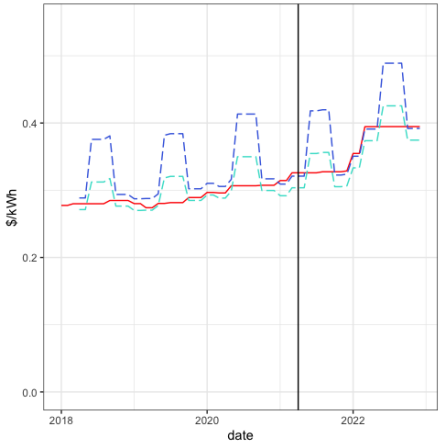
Trimming the Dataset

- Remove solar, subsidized/alternative cost plans, high/low usage households...
- Leaving $26,149$ households
- Approximately 90% have gas heating
- $16,668$ (63%) are on TOU pricing by the end of the transition program

back

Prices Over Time





Back

Summary Statistics

	Switch		Stay		Mean Delta	DiD
	Mean	**S.D.**	**Mean**	**S.D.**		
Pre-Rollout						
kWh	522.91	346.38	567.12	368.22	-44.21	
$	139.65	107.17	145.92	106.18	-6.27	
Peak kWh	146.26	109.27	165.92	123.53	-19.66	
Post-Rollout						
kWh	476.99	304.36	489.77	292.93	-12.78	31.43
$	168.64	133.58	177.58	133.13	-8.94	-2.67
Peak kWh	119.21	88.46	131.3	94.78	-12.09	7.57

Back

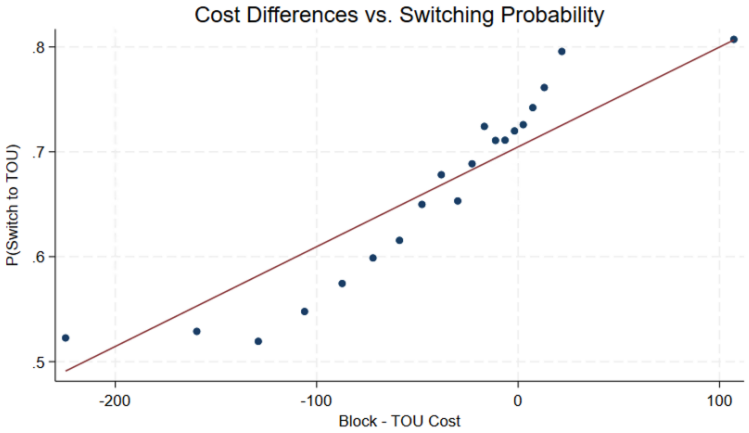
Pre-Rollout Costs by Month

	Mean	S.D.	Median	25th	75th
April Net Cost ($)	7.75	11.30	7.48	6.02	8.38
May	-7.99	22.55	-4.60	-18.37	2.93
June	-23.47	22.11	-19.32	-34.62	-10.27
July	-26.20	25.10	-21.39	-39.58	-10.93
August	-24.40	21.94	-20.92	-35.93	-11.22
September	-33.98	23.74	-29.87	-47.94	-16.05
October	7.41	9.60	7.21	5.87	8.24

Table: Net cost summary statistics by month, averaged over 2018 through 2020.

Back

Cost Differences and Switching



Back

Selection: Scheduling Uncertainty

Consumers may be uncertain of their schedule, or be unable to shift consumption around the peak period due to:

- Higher inter-day variance
- More consumption on-peak
- Uncertainty over work-from-home status post-Covid

Selection: Scheduling Uncertainty

- Data are normalized to mean 0, s.d. 1
- Includes wave, CZ FEs; cluster at zip
- 1 s.d. increase in household peak s.d. leads to about 5% decrease in likelihood of switching
- 2020 coefficients are all not significant

	P(Switch to TOU)	
(kWh)	**Using 2019**	**Using 2020**
Weekday, Peak Mean	-0.014	-0.050
	(0.042)	(0.049)
Weekday, Peak S.D.	-0.127	-0.016
	(0.036)	(0.042)
Weekend, Peak Mean	-0.005	0.064
	(0.042)	(0.049)
Weekend, Peak S.D.	0.093	-0.052
	(0.036)	(0.041)

Back

Selection: Work Uncertainty

	P(Switch to TOU)
During Covid	
Work Hour kWh	0.035
	(0.0320)
Off-Work Hour kWh	0.126
	(0.0530)
Weekend kWh	-0.097
	(0.0630)
Pre-Covid	
Work Hour kWh	-0.067
	(0.0280)
Off-Work Hour kWh	0.012
	(0.0520)
Weekend kWh	0.009
	(0.0580)

Selection: Bill Sensitivity

"Bill shocks" can occur when the previous bill is higher than expected; consumers may decrease current consumption based on receiving this information during their billing cycle. Define:

- Lagged Difference: $Cost_{t-1} - Cost_{t-2}$
- Deviation: $Cost_{t-1} - \overline{Cost_{m-1}}$

P(Switch to TOU)		
Lag Difference	**Bill Deviation**	**Bill Deviation Pct**
0.058	-0.050	-0.013
(0.009)	(0.009)	(0.008)

Back

Selection: Pre-Rollout Cost

Consumers deciding on whether to opt out via the portal could compare the costs of their previous usage under the TOU and block plan. Seeing negative value under TOU may have resulted in a higher likelihood of opting out, even if these costs may have been negated by gains during winter months. Define "net cost" as $Cost_{t,Block} - Cost_{t,TOU}$.

	P(Switch to TOU)	
	Summer Avg Net	**Winter Avg Net**
Coef.	0.182	-0.070
	(0.009)	(0.009)
Mean	-24.06	5.08
	20.21	10.20

Back

TWFE on Peak Consumption

	log(Peak kWh)	Peak %
Post x Switch	-0.021	-0.004
	(0.005)	(0.001)
R2	0.797	0.571
N	390,468	390,468
RMSE	0.278	0.034
Mean of Y	4.683	0.274

Back

TWFE With Seasons

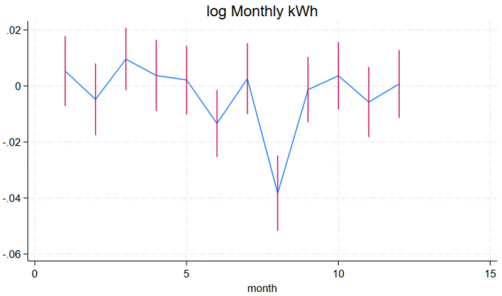
	log(Total kWh)	log(Bill $)
Post x Switch, Summer	-0.040	0.050
	(0.004)	(0.005)
Post x Switch, Winter	0.018	-0.041
	(0.004)	(0.004)
R2	0.848	0.847
N	547,853	547,855
RMSE	0.214	0.242
Mean of Y	6.033	4.716

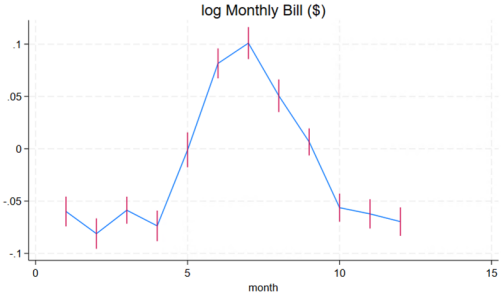
Seasons and Peak Consumption

	log(Peak kWh)	Peak %
Post x Switch, Summer	-0.074	-0.011
	(0.007)	(0.001)
Post x Switch, Winter	0.018	0.001
	(0.005)	(0.001)
R2	0.797	0.572
N	390,468	390,468
RMSE	0.277	0.034
Mean of Y	4.683	0.274

Back

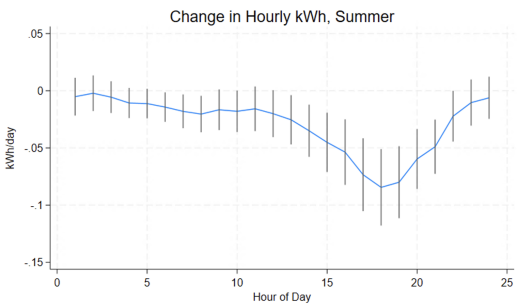
TWFE By Month

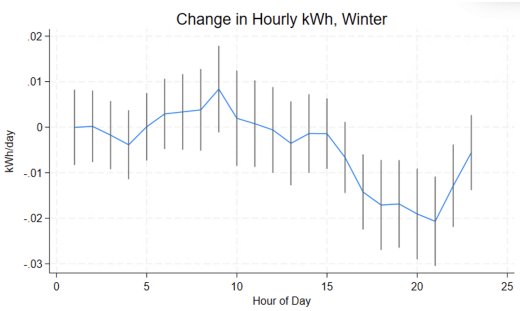




back

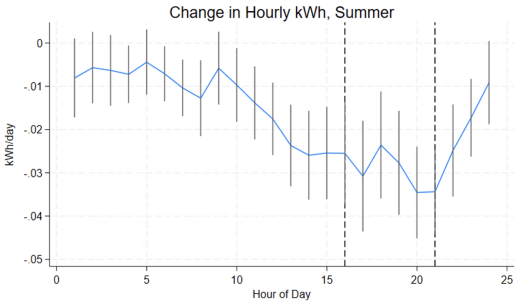
TWFE By Hour

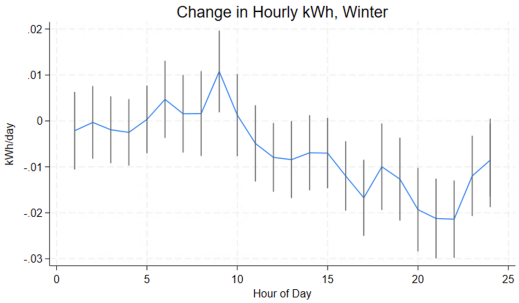




back

Match By Hour





back

Covid Effects

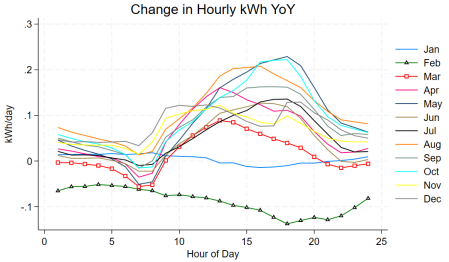


Figure: 2019 vs. 2020

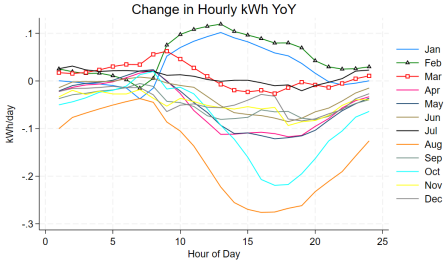


Figure: 2020 vs. 2021

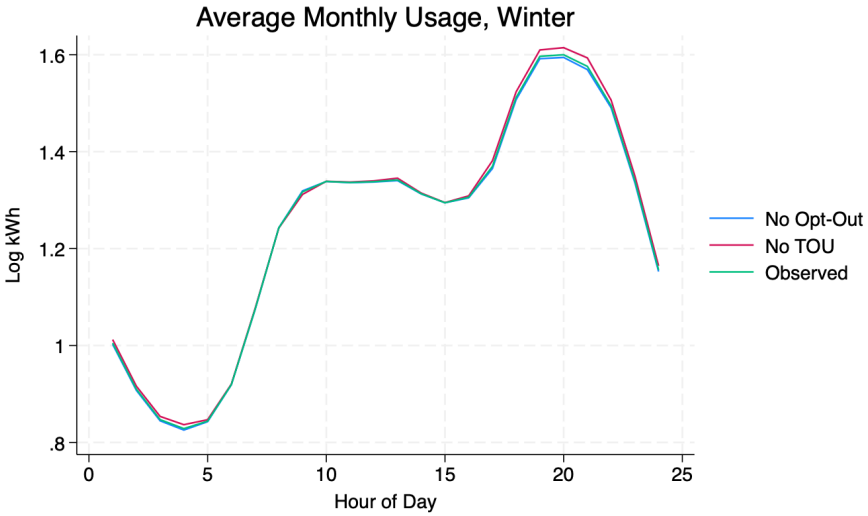
Back to rollout Back to Probit

Selected Variables

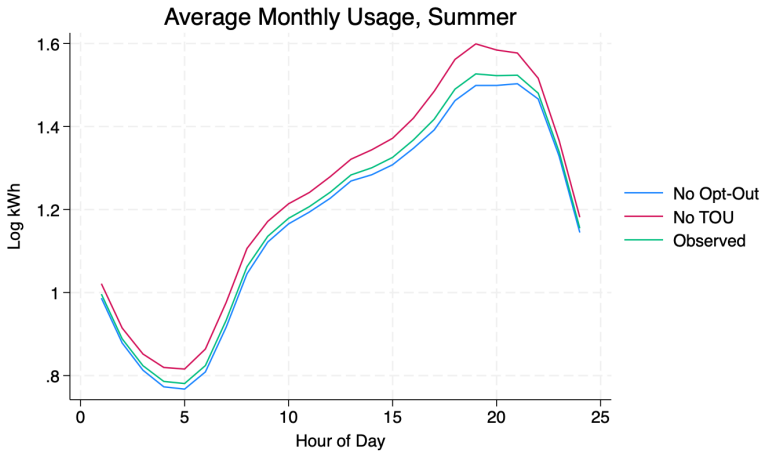
	Mean	SD	Median
Cost Difference, Summer	-21.65	13.51	-18.66
Cost Difference, Winter	4.74	3.10	4.53
Average Bill Deviation	-11.39	14.77	-8.78
Weekday Peak Average kWh, 2019	4.16	2.19	3.77
Weekend Peak Average kWh, 2019	4.28	2.24	3.91
Monthly kWh - Zone Average	-36.17	223.23	-73.06
Average Work-Hour kWh	105.56	63.44	91.22
Average Monthly Max Temp	70.24	8.22	64.23
Average Monthly Precipitation	0.07	0.06	0.09

Back

Hourly Changes, Winter



Hourly Changes, Summer



Back to Matching