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

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- 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

emissions graph

Policy Setting

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

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- Consumers that switch may face a salience issue
  - Habit adjustment may be slow

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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...
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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
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), Hinchberger et. al (2024), **Bernard et. al (2024)**
  - Contribution: Consumer response to dynamic pricing within billing cycles and across seasons

- Transitioning electric rates: Harding and Sexton (2017), Fowlie et. al (2021), Faruqui and Tang (2023), Ito et. al (2023), **Cahana et. al (2023)**, **Enrich et. al (2024)**
  - Contribution: Policy implementation for future TOU transitions

Roadmap

1. Walkthrough of electric utilities and program implementation

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3. Estimate the causal effect of the switch to TOU on consumption
4. Predict a counterfactual of load under forced TOU adoption

Background

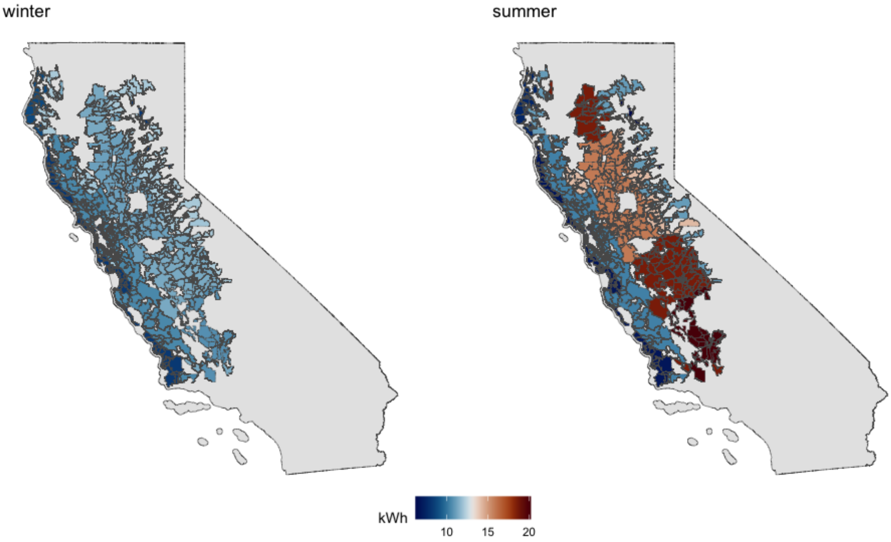
Electric Utilities: Plan Types

- 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

- Price tier thresholds are set using local climate conditions, organized into "climate zones"
- Tiering applies to cumulative usage during billing cycle
  - "Baseline": Median household's daily usage in each zone
  - Threshold kWh: $\mathit{baseline} \times \#\mathit{days}$
- Baselines differ in summer and winter
  - Summer: June through September
  - Winter: October through May
- Baselines also differ for gas heat ($\sim 90\%$ of customers) and electric heat

Electric Utilities: Climate Zones



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
  - Originally October 2020, delayed by Covid

covid

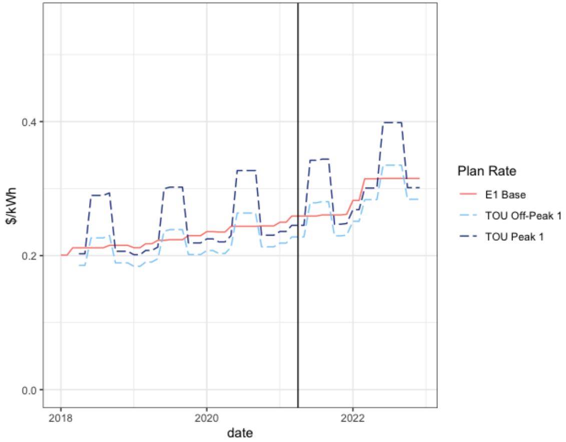
Electric Utilities: TOU Rollout

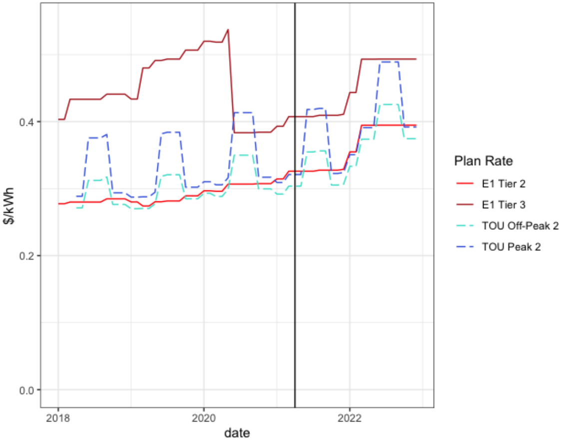
- Consumers were notified 4 months before rollout
- Nonresponse led to automatic opt-in
- Could compare previous bills under the block and TOU prices
- "Bill protection" for the first 12 months after transition

Electric Utilities: Prices

- Prices are set 1 to 6 months ahead
- Usually small changes, $< \$0.01$
- 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)
- Total yearly expenditure is nearly unchanged from original plan

Prices Over Time





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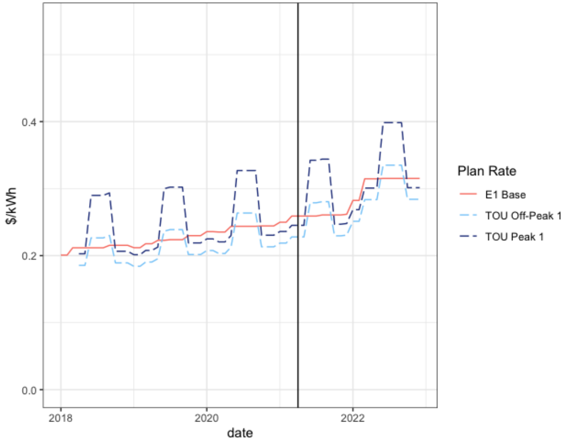
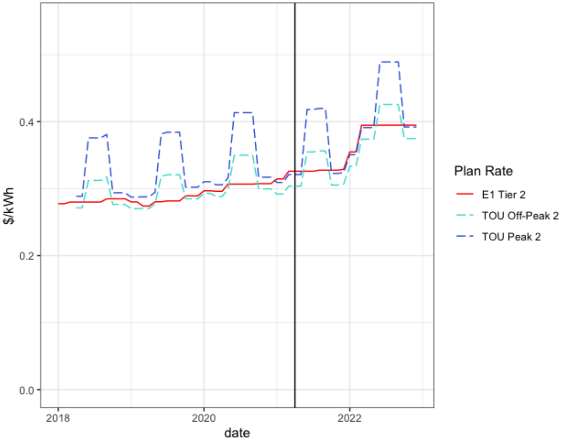
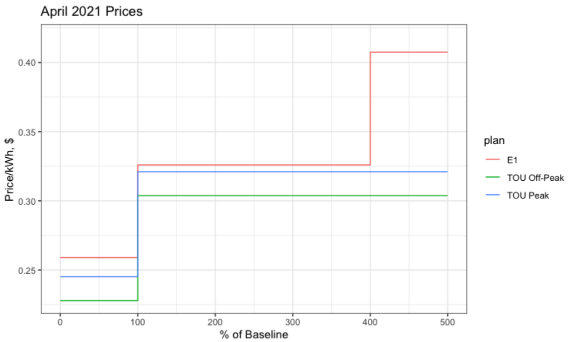
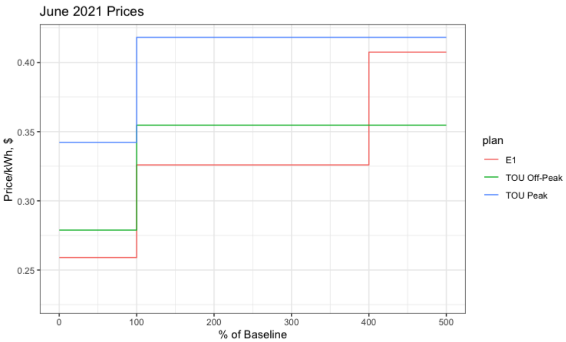




Prices By Usage





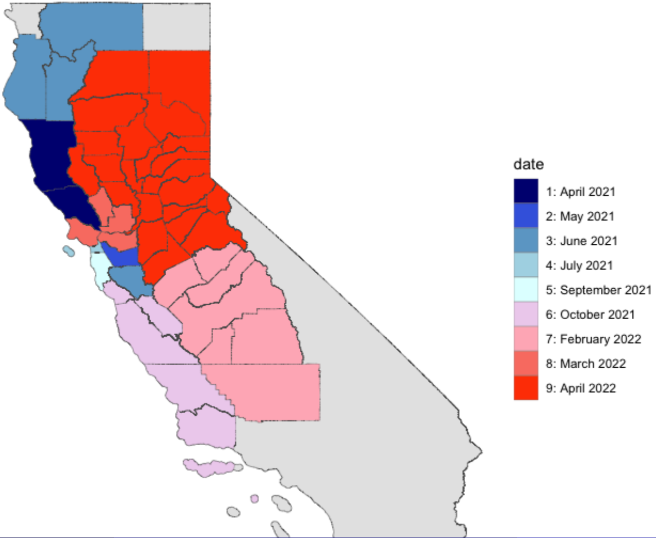
Data Sample

Primary Dataset from Pacific Gas & Electric

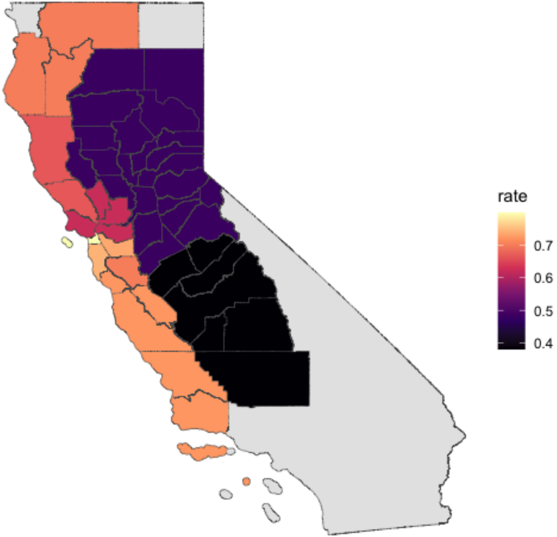
- 75,000 single-family households
- Zip code-level anonymization
- Could not switch homes during sample period
- Two primary datasets
  - Hourly meter data from 2018-2021
  - Monthly bills 2018-2022
- Includes: rate, hourly usage, home solar, income assistance indicators, climate zone, total bill amount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

Trimming

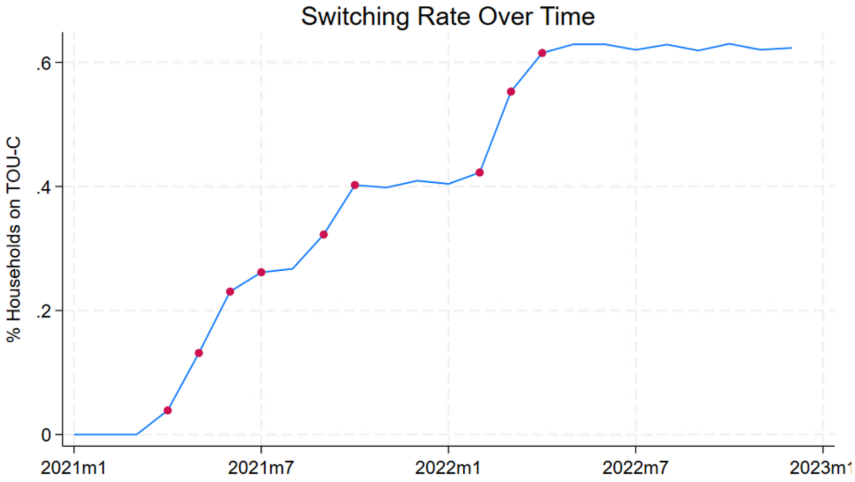
Program Rollout



TOU Transition Rates



Transition Rates Over Time



Pre-Rollout Summary Statistics

	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

Post-Rollout Changes

Post-rollout difference-in-differences shows...

- Mean total kWh $\uparrow$ 31.43
- Mean Peak kWh $\uparrow$ 7.57
- Mean Bill cost $\downarrow$ -2.67

Full table

Without accounting for season, geography, and other controls, TOU appears to induce higher consumption.

Empirical Framework

Framework: What informed consumer decisions?

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

- Customers face benefit of switching B_i and switching cost s for moving to TOU
- Consumers switch if $b_{iw} + b_{is} - s_i + \epsilon_i > 0$ and do not if they don't
- Attentiveness parameter $p_i \in P(s_i)$
- likelihood to invest in estimating switching cost
  - higher cost $\Rightarrow$ lower likelihood of investing in switch decision

Net Value of Switching

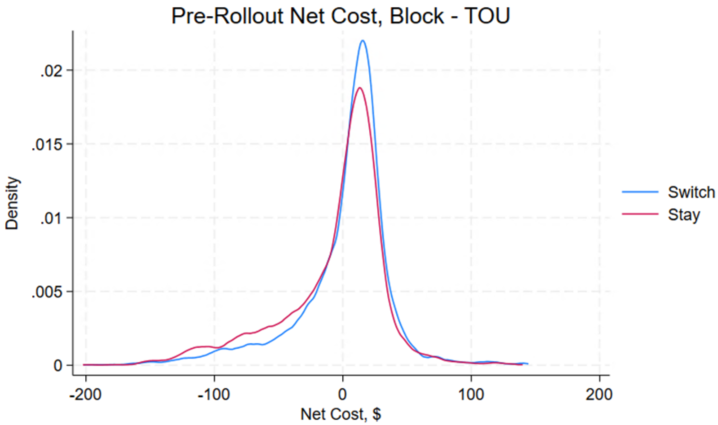
Net cost of switching: what customer *would have paid* on TOU in the 12 months before switch:

	Summer			Winter			Pre-Rollout Total		
	Mean	**S.D.**	**Median**	**Mean**	**S.D.**	**Median**	**Mean**	**S.D.**	**Median**
Switch	-19.59	18.86	-16.33	9.19	9.90	8.69	4.66	59.00	10.18
Stay	-24.33	17.28	-19.77	10.08	7.55	8.89	-3.74	53.97	5.69

Table: *Block* – *TOU* cost. Excludes the last 3 waves, May and September.

Cost Breakdown by Month

Distribution of Net Costs



Framework: Observations

- Only opt-out is observed directly; allowing switching not known
- Observe both opting out and switching regardless of positive/negative net value
- So both "optimal" and "sub-optimal" decisions observed
    - Inattentiveness appears to be a factor
- Note: Can switch electric plans once per year, little evidence of switching on/off after rollout

Selection

Was there Advantageous Selection?

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

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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

- Net cost, 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

Predicting Switching By Wave

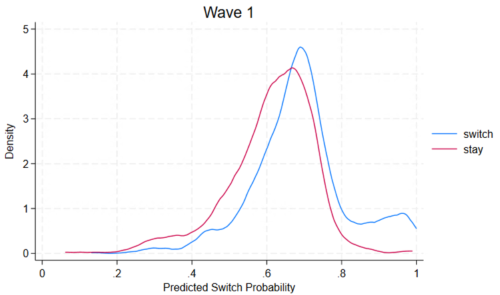

Figure: Some waves have distinct distributions between groups...

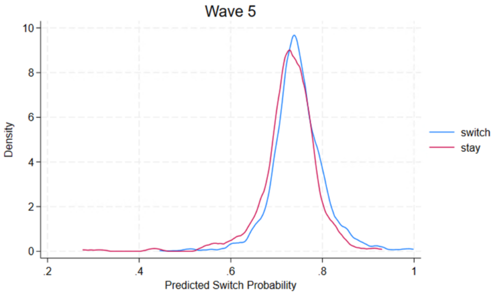

Figure: ... But others do not. This is particularly pronounced in the most temperate areas.

map

Treatment Effects

Treatment Effects: TWFE

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

$$Y_{it} = \beta_0 + \beta_1 basic_i + \beta_2 switched_i \times post_t + \gamma_i + \gamma_{jt} + \epsilon_{it}$$

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$$Y_{it} = \beta_0 + \beta_1 basic_i + \beta_2 switched_i \times post_t + \gamma_i + \gamma_{jt} + \epsilon_{it}$$

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

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

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

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

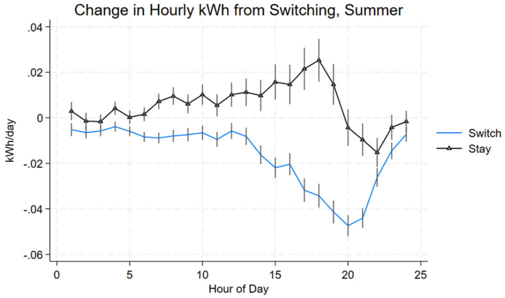
Seasonal

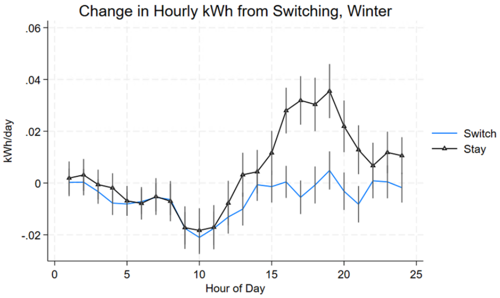
TWFE With Seasons and Periods

	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

Treatment Effects: Matching Estimator

Instead of TWFE, we can try to match consumers using similarities in their observables
Estimated equation:

$$ATE = \sum_{i=1}^{N_1} \frac{1}{N_1} \Delta Y_i - \sum_{j \in nbh(i)} \frac{1}{|nbh(i)|} Y_j$$

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

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

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.

Monthly Changes

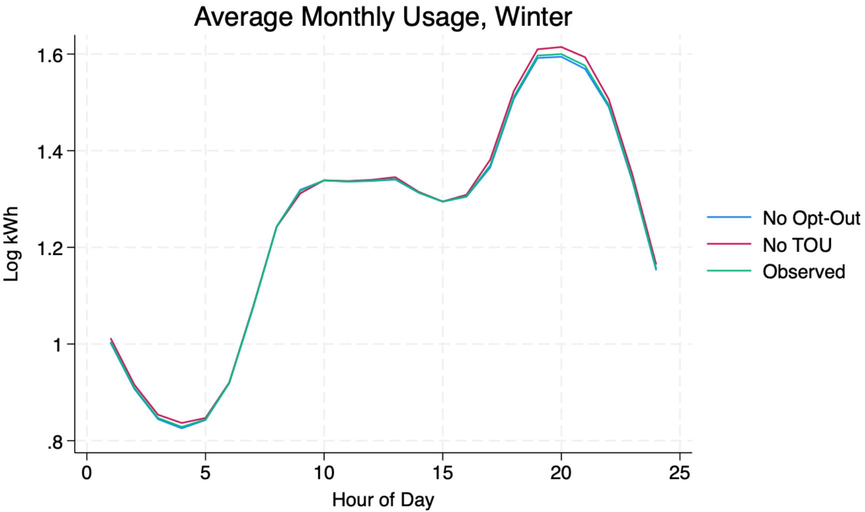
Counterfactual 1: No Opt-Out

	Summer			Winter		
	Mean	**SD**	**Median**	**Mean**	**SD**	**Median**
Total	463.1	298.4	392.56	442.05	282.29	388.25
Peak	129.76	97.25	102.94	116.82	75.17	102.82

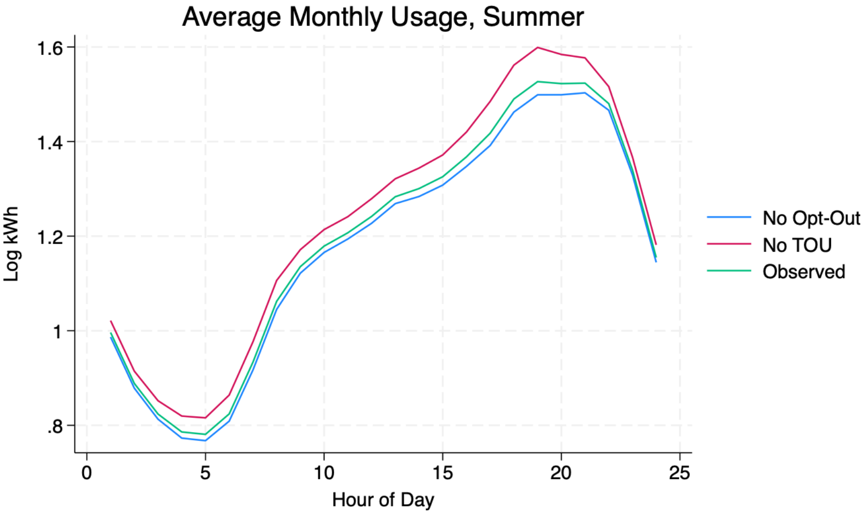
Counterfactual 2: No TOU

	Summer			Winter		
	Mean	**SD**	**Median**	**Mean**	**SD**	**Median**
Total	464	298.98	393.32	440.45	281.27	386.84
Peak	133.87	100.33	106.2	117.67	75.71	103.57

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

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

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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.

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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)

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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)

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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

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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
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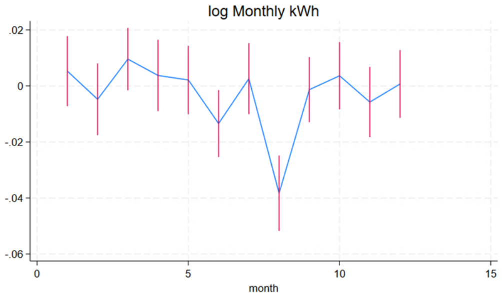
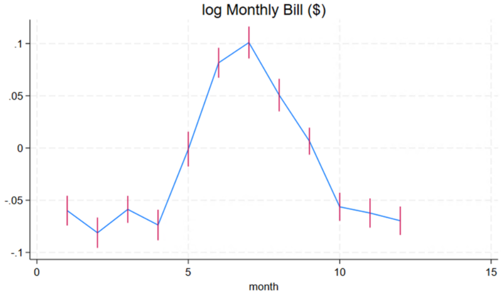
TWFE By Month





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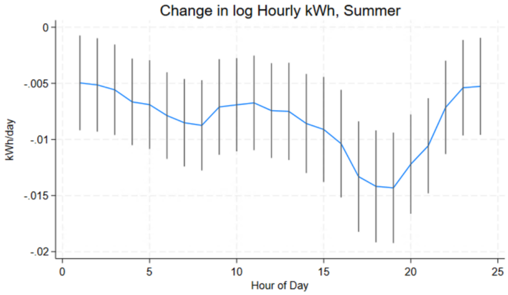
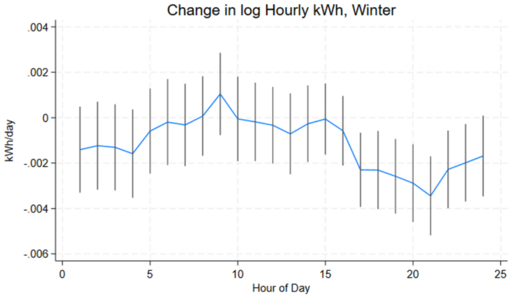
TWFE By Hour





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Covid Effects