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

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Motivation

- "Block pricing" has been the predominant pricing scheme for electric utilities since the 1930s, though new dynamic pricing schemes have risen in popularity in the past decade
- Dynamic pricing is preferable to flat pricing for utilities because it can accommodate time-based differences in demand, but getting consumers to switch to it is difficult
- Measuring the degree of consumer response to a switch in the pricing schedule is confounded by variations in geography, climate, and idiosyncratic preferences

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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?

Roadmap

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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

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3. The utility's "bill protection" program muted behavioral changes in the initial post-rollout period
4. While the program did achieve minor improvements in consumption, traditional difference-in-difference methods under-estimate the impact of the program on the treated due to advantageous selection

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)**

- 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)**

Contributions

1. Dynamic pricing: Analysis of how consumers respond to a change in their rates within billing cycles and across seasons

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2. Transitioning rates: A panel study of the effects of large-scale, non-experimental implementation of dynamic pricing on residential customers

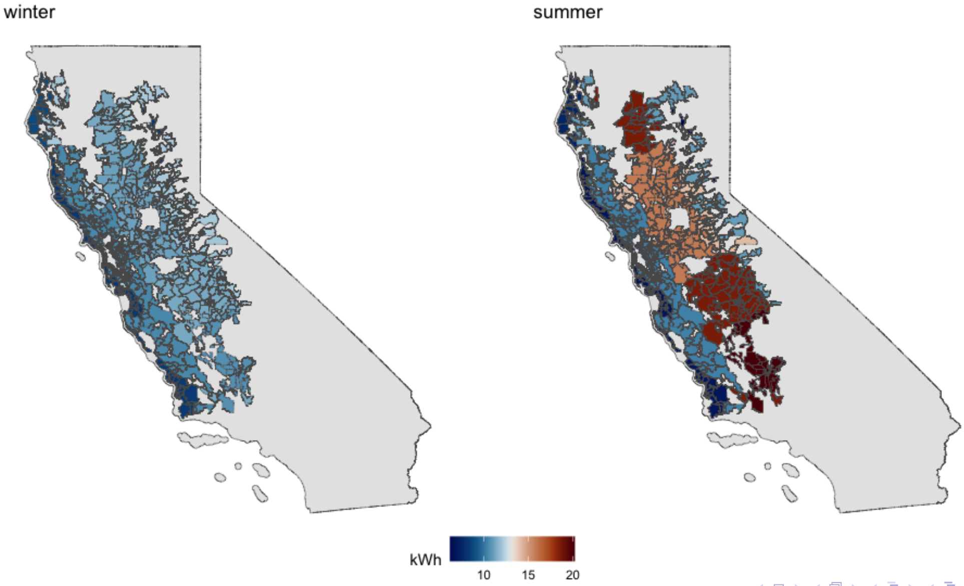
Electric Utilities: The Basics

- Most consumers face either flat tariffs or "block pricing" plans, where marginal price increases at specific usage thresholds
- Newer plans are dynamic in price: prices change in conjunction with demand
- Under "time-of-use" (TOU), price increases during high-demand hours set by the utility (usually the evening)
- The California Public Utilities Commission (CPUC) mandated that utilities transition their consumers to TOU from block pricing to TOU pricing, which began in 2021

Electric Utilities: The Basics

- Price tiers are set using local climate conditions and are calibrated to the median household's daily usage
- Applies to cumulative usage over the course of the month, using *baseline* $\times$ #*days*
- Baselines differ in summer (June - September) and winter (October - May)
- Baselines also differ for gas heat ($\sim$ 90% of customers) and electric heat

Electric Utilities: Climate Zones



Electric Utilities: TOU Program

- CPUC wanted to transition customers to TOU rates in order to promote energy conservation and lower aggregate peak-time consumption
- Approximately 40% of customers opted out of the program, leaving the other 60% as automatically opting in
- Rollout was done in 9 "waves," determined by groups of counties
- Rollout was implemented in April 2021 and ran through through April 2022

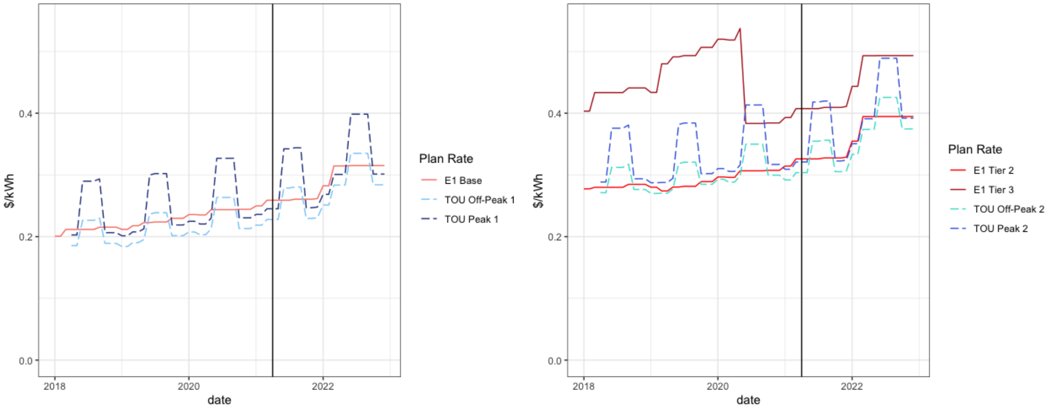
Electric Utilities: TOU Program

- Beginning 4 months prior to their county's transition date, consumers were notified of the transition program
- Nonresponse led to automatic opt-in
- Logging in to the portal would show a comparison of their past usage under the block and TOU prices
- PG&E promised "bill protection" for the first year that would reimburse consumers for bill increases for the first 12 months

Electric Utilities: Prices

- Prices are set anywhere from one to six months ahead
- Relatively small changes when they do happen
- TOU prices are seasonal in addition to dynamic
- Consumers face strictly lower TOU prices in winters (October—May)...
- ... But TOU prices are higher in the summer (June—September)
- Averaging across months and peak/off-peak usage, prices are nearly unchanged from block pricing

Prices Over Time



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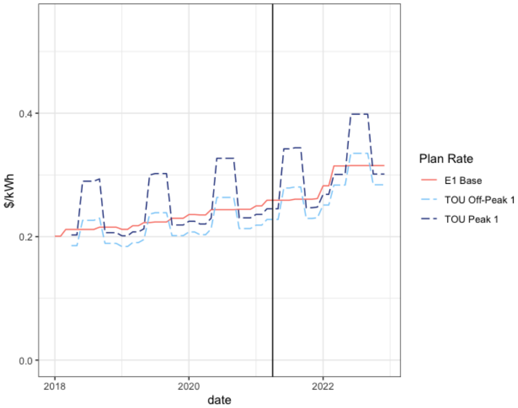
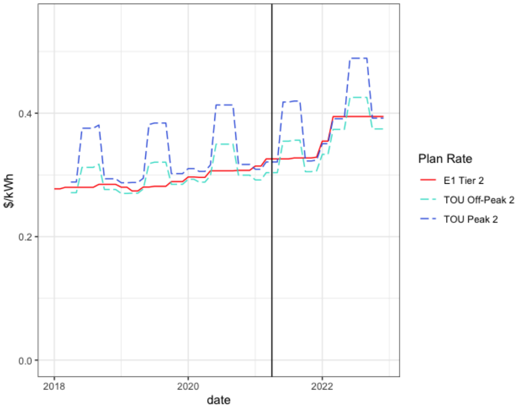
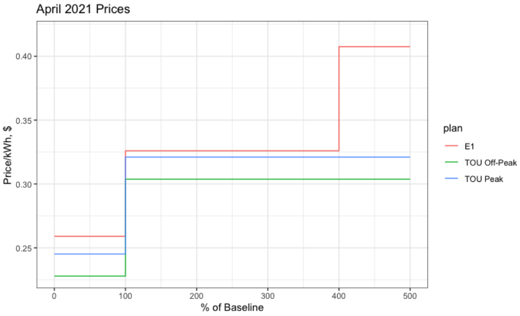
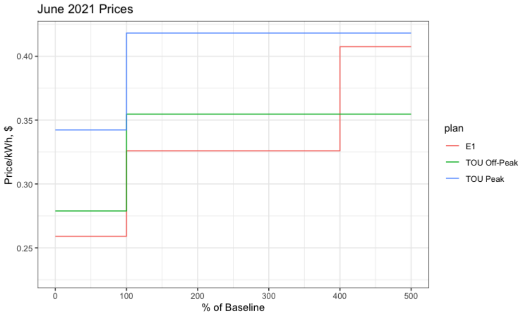




Prices By Usage





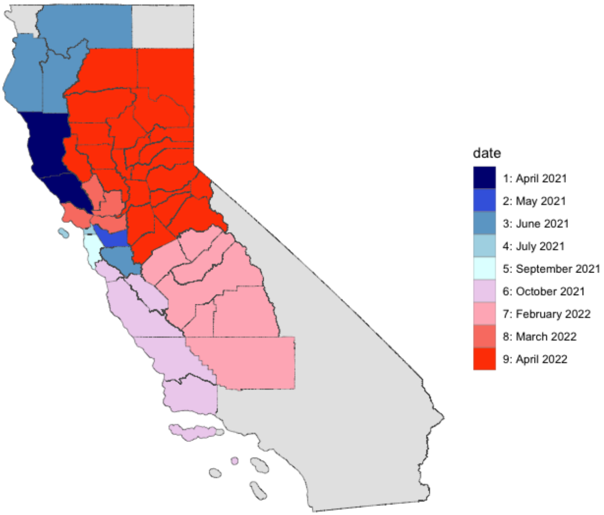
Data Sample

Primary Dataset from Pacific Gas & Electric in California

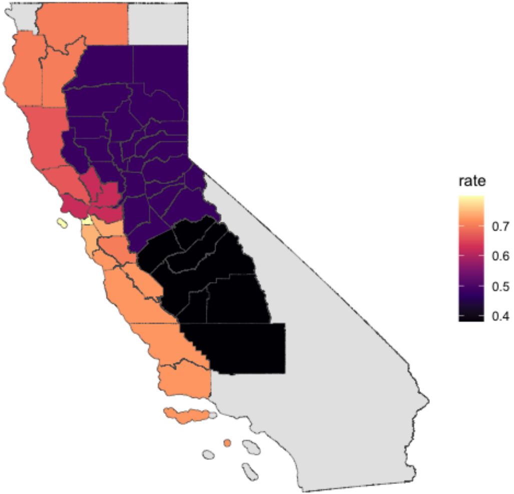
- Sample of 75,000 single-family households, anonymized to zip code level
- Customers do not move during sample and must be active for entire period
- Hourly meter data from 2018-2021, monthly bills 2018-2022
- Includes: rate, hourly usage, home solar, income assistance indicators, climate zone, total bill amount
- Missing: addresses, household characteristics, demographics

Trimming

Program Rollout



TOU Transition Rates



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

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 provided by PG&E
- 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

1. Consumer uncertainty over future consumption

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
- $Y_{ijk} = \mathbf{1}\{\text{Switch to TOU}\}$

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Possible Sources of Selection

1. Consumer uncertainty over future consumption
2. Sensitivity to changes in bills
3. Expected costs of TOU versus block pricing

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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

- Coefficients 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)

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

Some consumers may respond more strongly due to unexpected shocks in their bill from the previous period. "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 (0.009)	-0.050 (0.009)	-0.013 (0.008)

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

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 Is Difficult

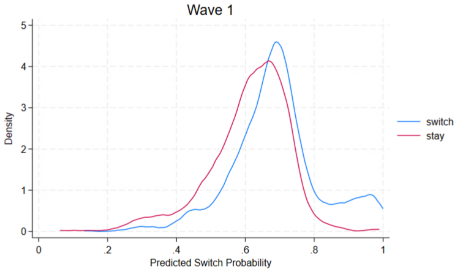

Figure: Some waves show more separation...

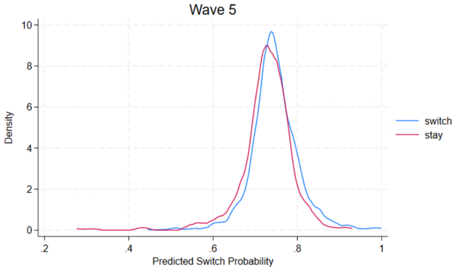

Figure: ... But others do not. This is particularly pronounced in the most temperate areas, suggesting that consumers may have been more indifferent between plans.

map

Treatment Effects: TWFE

For consumers that are transitioned, measuring treatment effects should be feasible through two-way fixed effects (TWFE)

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Model:

$$Y_{ijkt} = \beta_0 + \beta_2 post_{jt} + \beta_3 switched_{ik} \times post_{jt} + \gamma_i + \gamma_j + \gamma_t + \gamma_k +$$

- Y_{ijkt}: outcome for household i in climate zone k, subject to wave j, in time period t
- *switched* an indicator that i switches
- *post* an indicator that wave j has transitioned
- Note: omits 2020 and 2021 for composition reasons

is the outcome variable of choice

TWFE Estimates

	log(kWh)	log(bill \$)
Post x Switch	-0.010	-0.018
	(0.003)	0.004
Post	0.004	0.332
	(0.003)	(0.004)
HH FE	Yes	Yes
Wave FE	Yes	Yes
CZ FE	Yes	Yes
Cluster	Zip	Zip
N	868,560	868,560
R2	0.752	0.748
Mean of Dependent	6.085	4.762

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
3. Waves 6 through 9 have less than 12 months of post-transition data

TWFE: Seasonal Estimates

	log(kWh)			
	Summer, Short	**Summer, Long**	**Winter, Short**	**Winter, Long**
Post x Switch	0.001	-0.001	0.007	**0.016**
	(0.005)	(0.006)	(0.005)	(0.006)
Post	0.005	-0.004	-0.100	0.034
	(0.006)	(0.006)	(0.006)	(0.006)

	log(Bill $)			
	Summer, Short	**Summer, Long**	**Winter, Short**	**Winter, Long**
Post x Switch	**0.109**	**0.072**	**-0.051**	**-0.045**
	(0.006)	(0.007)	(0.006)	(0.007)
Post	0.227	0.375	0.247	4.555
	(0.007)	(0.007)	(0.006)	(0.001)

Treatment Effects: Matching Estimator

Instead of TWFE, we can try to match consumers using similarities in their observables. The ATE of the consumer's post-treatment consumption is

$$E[y_1 - y_0]$$

where y_1 is post-treatment and y_0 the pre-treatment period. Given that I have multiple periods for each consumer, I take the mean consumption across their pre- and post-periods.

I construct a propensity score that each consumer switches plans using the observables shown from the probit section. Consumers are matched from the treated and untreated groups according to their similarity in score, using 1 nearest-neighbor,

Treatment Effects: Matching Estimator

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 Results: kWh

Relative to TWFE, matching produces a consistent estimate of ATE across seasons and number of neighbors.

	Summer			Winter		
ATE	-10.867	-11.854	-11.612	-10.558	-10.596	-10.447
	(2.904)	(2.000)	(1.801)	(2.486)	(1.530)	(1.306)
Neighbors	1	5	10	1	5	10
N	10,590	23,340	23,340	23,446	23,446	23,446
Mean of Y	18	18	18	11	11	11

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	-2.093	-7.440	-7.823	-2.726	-1.929	14.813	-13.262	-9.141
	(2.794)	(3.051)	(2.489)	(3.172)	(1.018)	(1.273)	(0.931)	(1.284)
Neighbors	1	1	1	1	1	1	1	1
N	6,124	8,504	10,308	10,308	6,124	8,504	10,308	10,308
Mean of Y	-9.761	8.088	-40.265	34.069	9.055	64.394	6.146	55.107

Post-Estimation: Estimating Elasticities

- Using the observed ATE in consumption, we can estimate the elasticity for the switching households with respect to TOU pricing
- Despite large increases in price, consumption changed very little for switchers relative to their previously estimated amounts; elasticity is estimated near -0.01
- Forcing non-switching consumers onto TOU pricing would likely result in higher estimated ATE, assuming that selection story is correct
- Contemporaneous literature estimates that elasticities are frequently between -0.05 and -0.20, so this is much lower than other studies

	Stay	**Switch**
2019 Price	0.271	0.271
2022 Winter	0.366	0.369
2022 Summer	0.383	0.44
ATE Winter		-2.726
ATE Summer		-7.44

Concluding Remarks

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

Thank you!

I would appreciate any comments, questions, or feedback!

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