Home is Where the Charge Is: Electric Vehicle Adoption and Residential Electricity Demand

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Motivation

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- Utilities want to incentivize charging during periods of low grid usage ("off-peak")
- Problem 1: Household preference for charging times may clash with the utilities' preferences

Policy Setting

Pacific Gas and Electric (PG&E) introduced an electric vehicle charging plan, "EV-A", in 2014

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- Problem 2: The utility does not know who has an EV but has not opted in
  - No coordination with the DMV or dealerships
- They suspect that opt-in is low, but they have no way to verify

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2. What is the trade-off between in-home usage costs and charging?
3. Would households benefit from automatic opt-in?

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3. Households don't opt in because disutility from changing schedules is high
    - Automatic opt-in would lead to higher loss than scrapping the program altogether

Relevant Literature

- Electric vehicle charging demand: Li et al. (2017), Burlig et al. (2021), Springel (2021), Underwood (2021), Dorsey et al. (2022), Underwood (2023), Rapson and Bushnell (2024)
  - **Contribution**: Complement existing literature by focusing on home charging

- Time-of-use and electric plan choice: Fowlie et al. (2021), Ito et al. (2023), Cahana et al. (2023), Enrich et al. (2024)
  - **Contribution**: Model time-of-use plan choices among electric vehicle owners

Roadmap

1. Overview of the program

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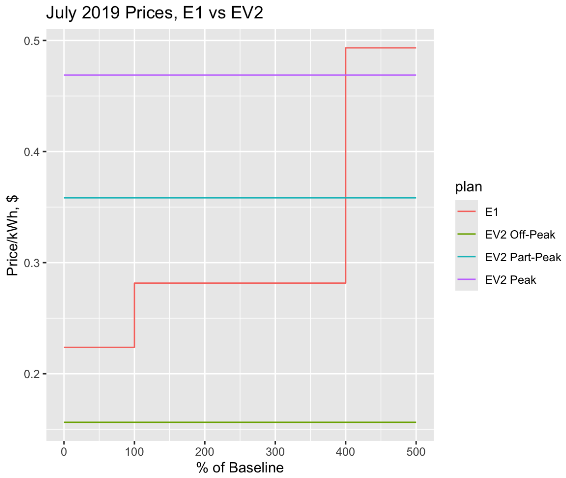
5. Predict the effects of a counterfactual with automatic plan opt-in

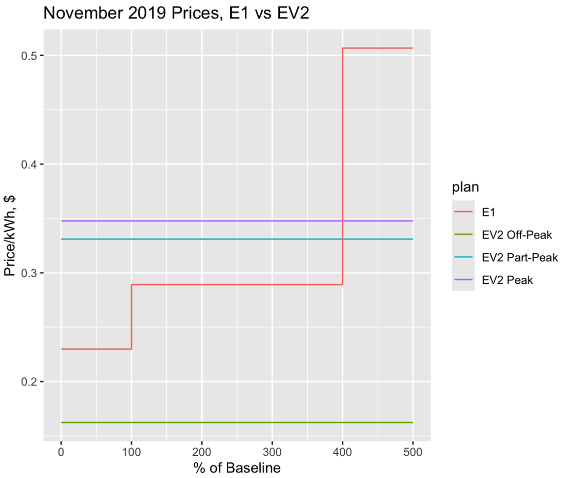
Background

EVs and Electric Utilities

- Most electric plans in the US are block plans, with prices increasing at usage thresholds
    - Block plans also have geography dependent thresholds to accommodate climate differentiation
- On PG&E's EV plan, prices are static across days, but are dynamic across hours, with three different periods and prices
    - No climate zone differences, but prices are seasonal for all users

Prices By Usage





By Time

EV Plan Periods

	Time of Use	Hours	Charge
EV-A	Peak	2:00pm - 9:00pm M-F 3:00pm - 7:00pm Weekends, Holidays	\$0.51832
	Part-Peak	7:00am - 2:00pm M-F 9:00pm - 11:00pm M-F	\$0.28096
	Off-Peak	Else	\$0.13452
EV2-A	Peak	4:00pm - 9:00pm every day	\$0.46883
	Part-Peak	3:00pm - 4:00pm 9:00pm - 12:00am	\$0.35834
	Off-Peak	Else	\$0.15633

Visual

Structural Model

Modeling Plan Choice

I model the household's choice of electric plan after they purchase an electric vehicle as a discrete choice:

- Households have perfectly inelastic demand for electricity in the home
- The household chooses from two plan options
- In each period, they determine their optimal plan and enroll in it for the month

Plan Pricing

The default (block) plan has three tiers of pricing p depending on usage k:

$$C_t(q) = \begin{cases} p_0 \cdot q, \text{ for } q \leq k_0 \\ p_0 \cdot k_0 + p_1 \cdot (q - k_0), \text{ for } k_0 < q \leq k_1 \\ p_0 \cdot k_0 + p_1 \cdot (k_1 - k_0) + p_2 \cdot (q - k_1), \text{ for } q > k_1 \end{cases}$$

The EV plan has prices that vary depending on intra-day periods:

$$C_t(q) = r_{pk} \cdot q_{pk} + r_{pp} \cdot q_{pp} + r_{op} \cdot q_{op}$$

Let $r_{pk} \leq p_0 \leq p_1 \leq r_{pp} \leq r_{op} \leq p_2$.

Block Plan Utility

Consumer i's utility in period t on the default block plan b is

$$U_{i,t,b} = -C_{i,t,b} + \epsilon_{i,t,b}$$

- $C_{i,t,b}$ is cost for consumer i at time t on block plan b
- $\epsilon_{i,t,b} \sim T1EV(0, \sigma)$ is an idiosyncratic taste shock

EV Plan Utility

Consumers can save money on the EV plan by shifting Δq consumption away from the peak periods to off-peak periods, $\Delta q \in [0, q_{pk}]$. Utility is

$$U_{i,t,ev} = -C_{i,t,ev} - \psi \Delta q_{i,t}^2 + \epsilon_{i,t,ev}$$

- Cost $C_{i,t,ev}$
- ψ is disutility from shifting consumption to off-peak hours
- $\epsilon_{i,t,ev} \sim T1EV(0, \sigma)$ is an idiosyncratic taste shock

Household's Maximization Problem

Consumers maximize their utility in each period by choosing a plan j:

$$j^* = \arg\max_{j \in b, ev} U_{i,t,j}$$

Consumers only choose the EV plan if its utility exceeds that of the default:

$$U_{i,t,ev} > U_{i,t,b}$$

$$-C_{i,t,ev} - \psi_i \Delta q_{i,t}^2 + \epsilon_{i,t,ev} > -C_{i,t,b} + \epsilon_{i,t,b}$$

Data

Data

Primary Dataset from Pacific Gas & Electric (same as Kirwin (2025))

- 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 the Data

- Limit analysis to 2018-2019 to avoid Covid lockdown period
- Remove EV owners who are always on the EV plan, leaving 154
- Begin with 10% sample of non-EV-plan households; identify 725 potential EV owners
- Current: 879 households with 24 months of observations each

Summary Statistics

EV bills tend to cost more and have substantially higher usage:

		N	Mean	S.D.	Median
E1	kWh	19,302	503.09	353.70	422.7
	$		124.72	103.77	99.05
EV	kWh	2,275	772.94	487.36	643.08
	$		172.98	113.63	143.02

Plan Costs By Type

Ever on EV plan	**N**	**Mean**	**SD**	**Median**
Block Plan Cost	3,783	$138.43	$113.08	$110.56
EV Plan Cost	3,783	$134.00	$96.59	$111.49

Never on EV Plan	**N**	**Mean**	**SD**	**Median**
Block Plan Cost	17,794	$132.97	$115.90	$103.49
EV Plan Cost	17,794	$130.67	$101.86	$104.82

Event Studies

How does buying an EV change consumption?

- If charging at home, charging volume should reflect driving distance
  - DOE: $\sim$ 80% of charging volume is done at home
- Charging is likely done overnight before work
- Consumers can opt in to the EV plan at any time after they purchase it

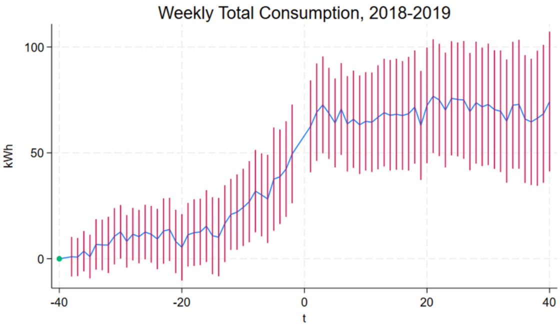
Event Study Estimation

To test this, I run the following:

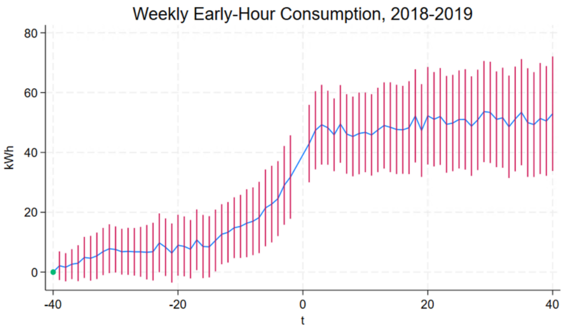
$$Y_{it} = \beta_0 + \sum_{\tau=-40}^{\tau=-2} \beta_t \mathbf{1}\{t = \tau\} + \sum_{\tau=0}^{\tau=40} \beta_t \mathbf{1}\{t = \tau\} + \gamma_{y,m} + \gamma_{i,m} + \gamma_{i,y} + T_t + \epsilon_{ijt}$$

- K_{ijt} weekly energy consumption
- $\gamma_{i,m}$ interacted FEs for customer and month
- $\gamma_{i,y}$ interacted FEs for customer and year
- T_t linear time trend for sample week
- Sample: All EV plan households, 10% sample of others

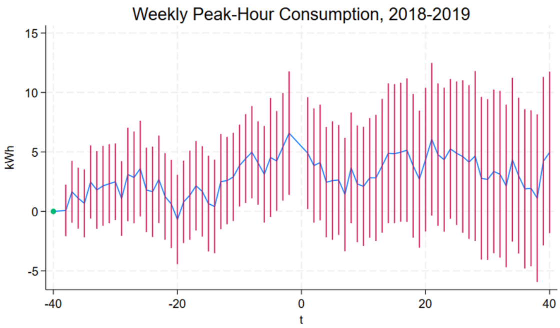
Event Study: EV Plan Opt-in



Event Study: Early Hours



Event Study: Peak Hours



All years

Event Study Takeaways

- EV owners purchase the car but don't switch plans for a few months afterwards (on average)
- Most of the increase in consumption happens overnight
- Peak-hour consumption increases before the plan and recedes after switching

Detecting Unknown EV Owners

We've established how consumption changes among plan-switchers

- Assumption: Other EV owners who charge at home but *don't* switch plans should see similar increases in overall consumption
- Using structural breaks, I test for other households experiencing a similar increase in consumption

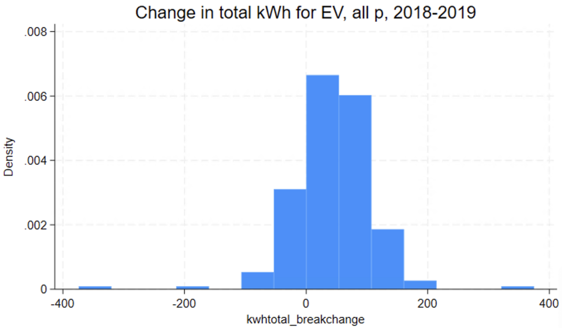
Structural Break Testing

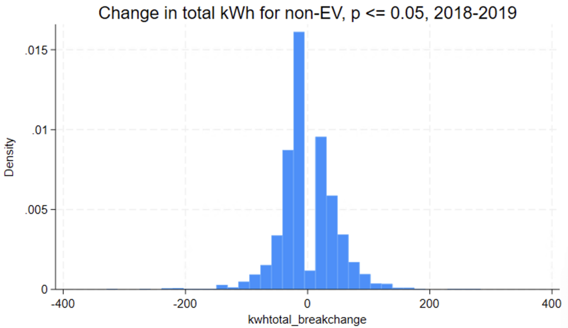
I test for a structural break of unkown date τ in each household's time series of consumption using

$$y_t = \beta_0 + \beta_1 \mathbf{1}\{t >= \tau\} + \epsilon_t$$

- y_t is the household's de-trended consumption in week t
- $\mathbf{1}\{t \geq \tau\}$ takes value 1 for weeks after a break occurring at τ
- τ is the supremum-Wald maximizing date from the available observations

Post-Break Differences





Post-Break Differences

- Households on an EV have distributions skewing to the right
- EV households: average $40.32kWh/wk$ increase, median $43.37kWh/wk$
  - $31.32kWh/wk$ average and $28.28kWh/wk$ median in early hours
- non-EV households: keep only households with a positive change in consumption

Inferring EV Purchase Date

We want to infer the date of EV purchase in order to model the decision to opt in to the EV plan

- Ideally, the estimated structural break should occur before opting into the EV plan...
- But for some households, the break occurs up to ~ 10 weeks after their plan switch
- Rule of thumb: Structural break is within $[-30, 10]$ weeks of plan adoption to be eligible for structural model
- For non-switching households, take break date as EV purchase date

Final dataset: 154 EV-plan households, 725 other households

Estimating Δq

Since Δq is not directly observed, I estimate it using two-way fixed effects starting from the household's estimated purchase date of the car:

$$y_{i,t} = \beta_0 + \beta_1 \mathbf{1}\{i = i'\} + \beta_2 post + \Delta q \mathbf{1}\{i = i'\} \times post + \epsilon_{i,t}$$

where

- $y_{i,t}$ is household i's early-hour consumption in week t, de-trended by climate zone and month
- $\mathbf{1}\{i = i'\}$ is an indicator for EV household i'
- *post* is the period after household i' purchases their EV
- Interaction coefficient Δq is the change in consumption for household i' from purchasing the car

Summary Stats

Summarizing

From household consumption trends, I am able to

- Show how household consumption changes after EV purchase
- Use these trends to infer which other households likely have an EV
- Estimate the household's willingness to shift consumption across periods of the day

Model Estimation

Frame Title

Recall that consumers choose the EV plan if

$$U_{i,t,ev} > U_{i,t,b}$$

Or, rearranging,

$$\epsilon_{i,t,ev} - \epsilon_{i,t,b} > C_{i,t,ev} + \psi \Delta q_{i,t}^2 - C_{i,t,b}$$

Choice Probability

Using $\epsilon_{i,t,j} - \epsilon_{i,t,k} \sim Logistic(0, \sigma)$, we can obtain choice probability

$$Pr(\epsilon_{i,t,j} - \epsilon_{i,t,k} > C_{i,t,ev} + \psi \Delta q_{i,t}^2 - C_{i,t,b}) = \frac{1}{1 + \exp(\frac{C_{i,t,ev} + \psi \Delta q_{i,t}^2 - C_{i,t,b}}{\sigma})}$$

Estimation

I estimate the model using maximum likelihood, with log-likelihood function

$$log(\mathcal{L}(\psi,\sigma)) = \sum_i [y_i log(P_i) + (1-y_i) log(1-P_i)]$$

where

- y_i is household i's choice of plan
- P_i the choice probability

Estimation

Estimation via MLE yields

- $\psi = 811.49$
- $\sigma = 25.84$
- Hessian is non-invertible, so covariance is near-zero and standard errors are unstable

Probit

Counterfactual

Counterfactual Policy

Question: What would happen to utility under (1) automatic opt-in or (2) no EV plan was offered?

Approach:

- Estimate expected utility under the household's choice
- Estimate loss using deterministic utility

Counterfactual Results

Comparing estimated welfare loss under counterfactual simulation:

	Mean Loss	**Median Loss**	**Total Loss**
No Change (Utility)	20.68	21.81	446,222.88
Forced Block Plan	154.61	126.82	3,335,980
Forced EV Plan	133619.42	5093.68	2,883,106,304

Conclusion

Concluding Remarks

What I've done:

- Model consumer choices for electric utility plans after purchasing an EV
- Leverage behavioral evidence from known EV users to infer the overall rate of EV ownership, finding opt-in to the plan is about 17.5%
- Estimate the theoretical model, finding that disutility from the timing of consumption is high

Policy Takeaways

- The current EV program is effective in incentivizing a reduction in peak-hour consumption for households that willingly opt in
- Decreasing the disutility for other households may lead to higher take-up

Thank you!

I appreciate your comments, questions, and feedback!

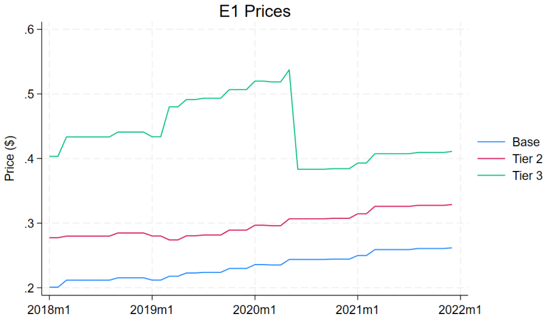
Future Work

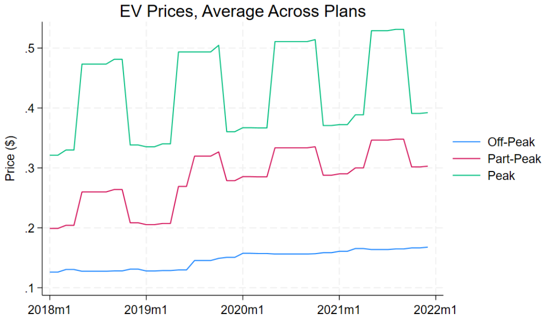
Modeling refinement:

- Households have a lock-in period when choosing a plan that needs to be considered
- Incorporate the option to shift consumption from peak to part-peak, or weekdays to weekends
- May be necessary to consider attentiveness among never-EV-plan households
- Possible endogeneity in Δq measurement

Appendix

Prices By Time





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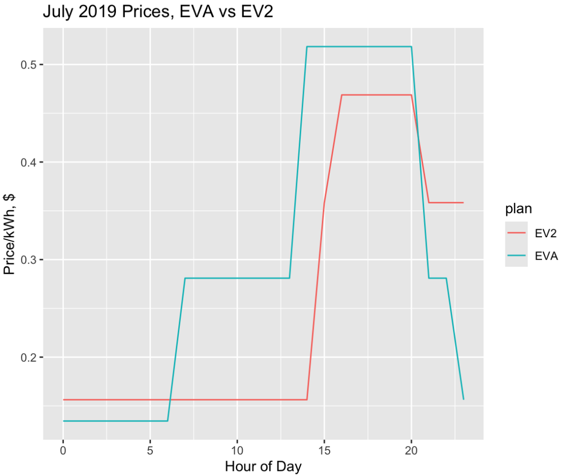
EV2 vs EV1



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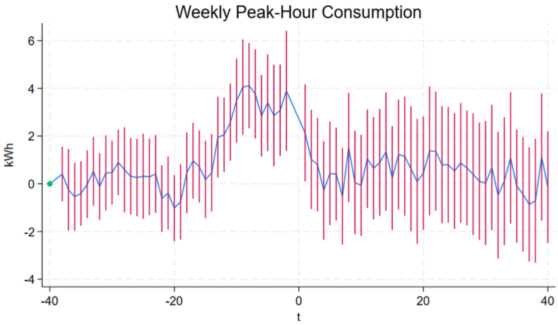
Peak Event Study, All Years



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Δq Summary

EV-plan households shift slightly less consumption to the early hours on average, but medians are nearly equivalent:

	N	Mean	SD	Median	25%	75%
Ever on EV plan	154	-0.883	15.176	1.047	-1.718	2.692
Never on EV plan	725	1.269	12.195	1.147	-1.035	3.501

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Probit

To supplement the MLE, we can also estimate this model as a simple probit:
$P(y_{i,t} = 1|X) = \Phi(X^T \beta)$
where

- $y_{i,t}$ is the household's decision to switch or not
- X are plan costs and the estimated shift Δq

Probit Results

	Standard	**No Constant**
E1 Cost	1.1135	.7631
	(.0354)	.0285
EV Cost	-.9256	-.6050
	(.03911)	(.0280)
Δq	-.0139	.0012
	(.0097)	(.0012)
N	21,577	21,577
LL	-6478.96	-14489.09

Back to MLE