Take the Load Off: Effort and Technology as Determinants of Electricity Demand Response

Megan Bailey, University of Calgary
David Brown, University of Alberta
Blake Shaffer, University of Calgary
Frank Wolak, Stanford University

This research is supported by excellent research assistance from Mallika Sharma (U Calgary) and funding from the Canada First Research Excellence Fund as part of the University of Alberta's Future Energy Systems research initiative and the University of Calgary's Global Research Initiative, the Dept. of Economics (U Calgary). We are grateful to our partner electric utility for sponsoring and managing this field experiment.

Future Role of Flexible Demand

1. **Need**
   - Higher shares of renewables $\Rightarrow$ less supply side flexibility and more net demand variability
2. **Potential**
   - Rapid growth of electric vehicles (and other forms of electrification) $\Rightarrow$ bigger magnitude of flexible load... and more need for demand response
3. **Ability**
   - Control and telemetry technology are making it cheaper and easier to respond

How Best to Promote Demand Response?

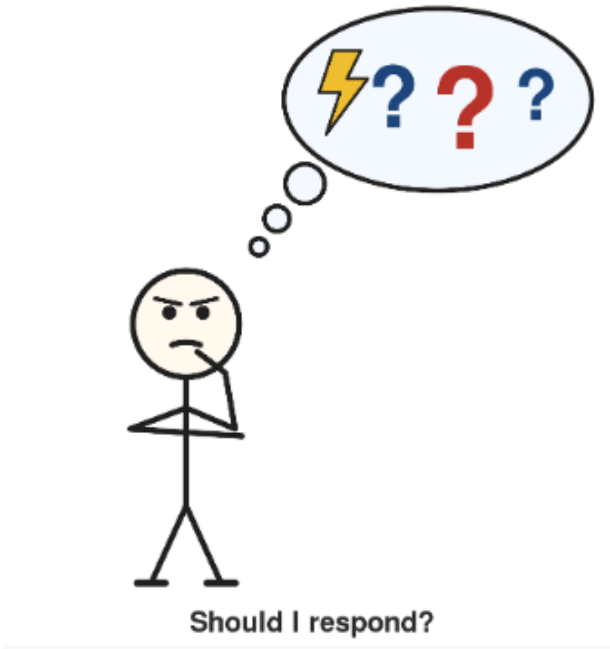
- Benefits of time-varying pricing are well-known (Boiteux, 1960; Borenstein and Holland, 2005)
- Evidence households respond to time-varying rates (Faruqui et al., 2014; Harding and Sexton, 2017; Bernard et al., 2026)
- But there are barriers to responsiveness:
  - Adjustment costs and information acquisition (Fabra et al, 2021)
  - Inattention (Sallee, 2014; Schneider and Sunstein, 2017)
  - Difficulty understanding price signals (Ito, 2014; Shaffer, 2020)
- Enabling technologies + automation can help when combined with pricing (Bollinger and Hartman, 2020; Blonz et al., 2025; Bailey et al., 2026; Metcalfe et al., 2026)
- Technology alone may not be sufficient (Brandon et al., 2022)

What We Do

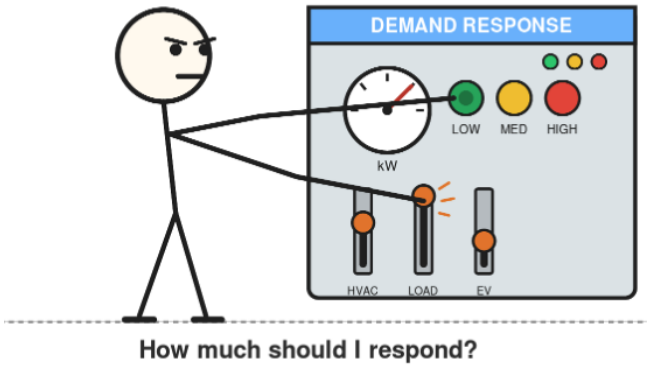
- How much of the barrier to demand response is effort/time, and can technology overcome it?
  - Many DR programs involve "picking up pennies"
  - Focus: Opportunity cost of time (Becker, 1965)
- Randomized control trial (framed field experiment)
- *Within-subject* design
  - Individually randomize "peak events"
  - Estimate household-specific treatment effects
- Consider several DR programs:
  1. Behavioral with manual response (active)
  2. Behavioral with load control tech (active)
  3. Automated with centralized load control (passive)

Two Stages of Consumer Response

Step 1: Should I respond to this event?



Step 2: Condition on responding, by how much?



Field Experiment: Peak Events

- We partnered with a large Canadian electric utility
- Treatment of Interest: Demand response to "peak events"
- *Randomized* event schedule across households
  - Event time: Weekdays, morning (7-10am) or evening (5-8pm)
  - Event type: "Peak" or "High Peak" (high incentive payment)
  - HHs generally receive 2-3 events per month (1 is "High Peak")

Field Experiment: Peak Events

- Households notified (in an App) 21 and 2 hours prior
- Incentives: based on reduction from household's baseline
  - Regular Peak: (10%, 30%, 50%) = ($1, $2, $3)
  - High Peak: (10%, 30%, 50%) = ($1, $3, $6)
- Incentives translate to $1.11 to $2.22 per KWh reduction for the average household
- 17 months: Feb 2022 - June 2023
  - *30,502 household-event days*

Field Experiment: Demand Response Programs

- Households recruited to the Utility's App - 9,020 HHs
- Randomize eligible HHs into demand response programs
  - *Offers made to 1,661 households* Details

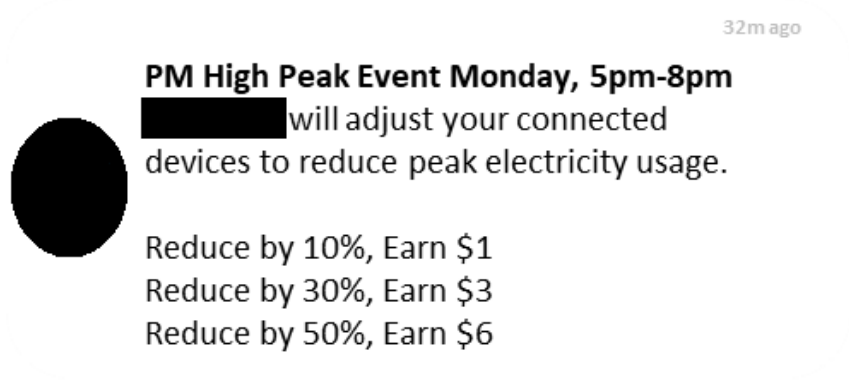
	DR control	Load control tech	Price incentive	Usage info
Central	Utility*	✓	✓	✓
Tech	HH	✓	✓	✓
Manual	HH		✓	✓
Control	HH			

*HH has ability to opt-out

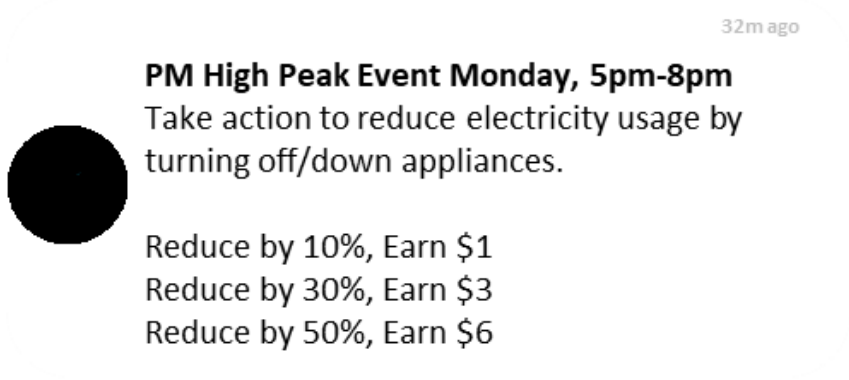
Load Control Devices Real Time Info

User Experience: Peak Event Messaging

Central group 21hr notification with incentives

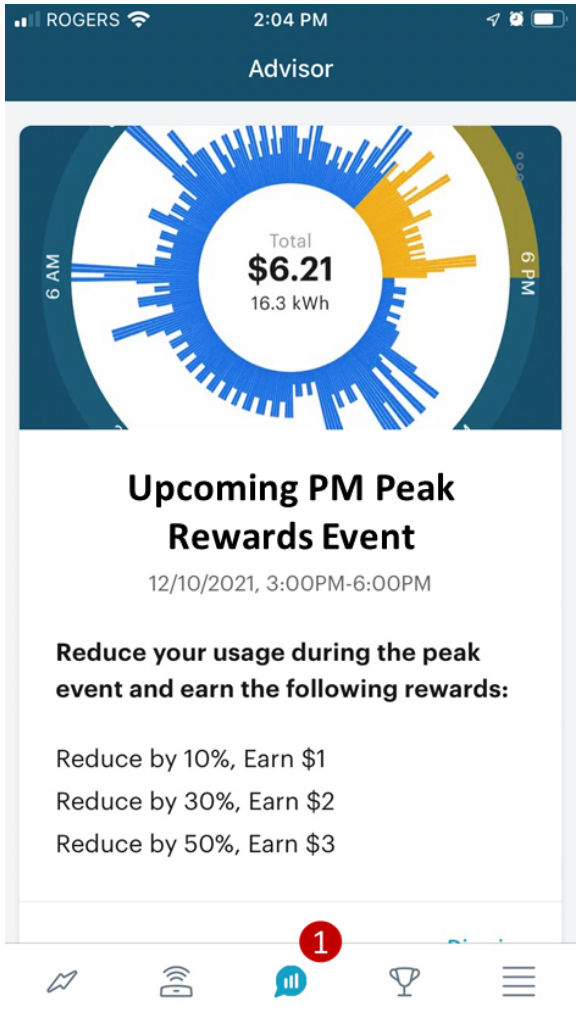


Tech/Manual group 21hr notification with incentives

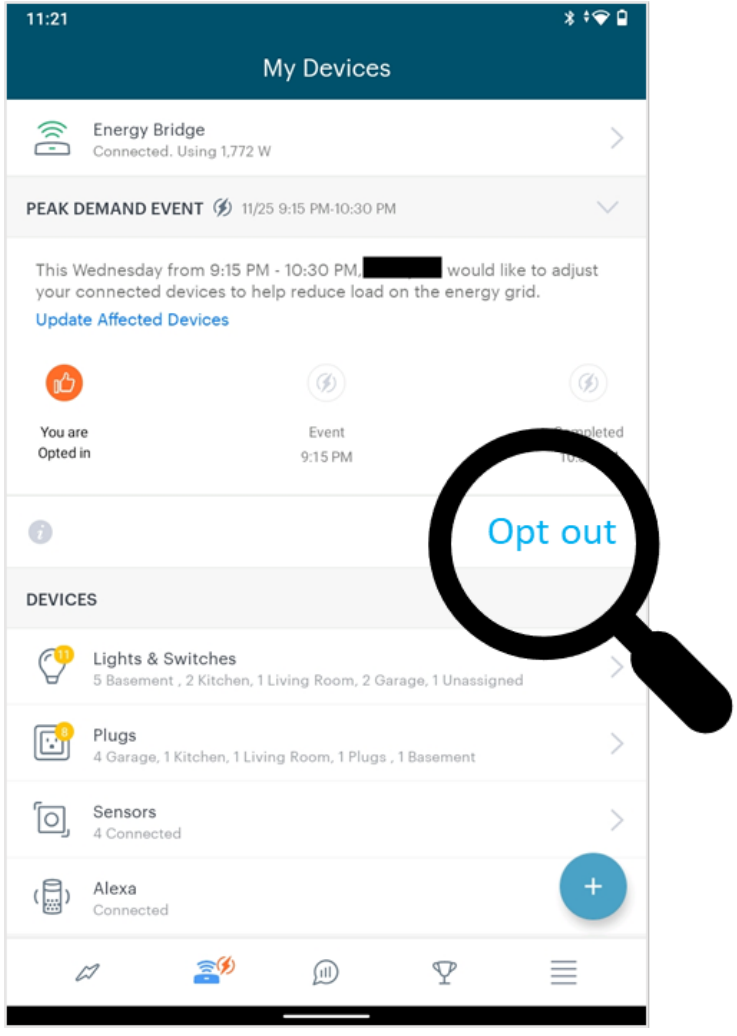


User Experience: In-App Message & Central Devices

In-App notification



Central - Opt out



User Experience: Tech Opt-In

All smart devices, including smart plugs and load controllers can be set up and controlled through the "My Devices" page in the [redacted] app.

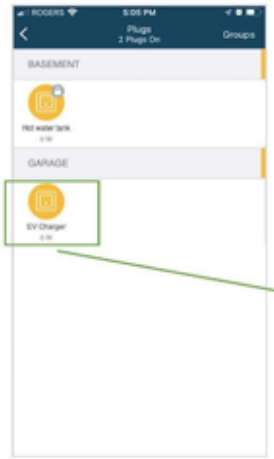
Select this icon  at the bottom of your app to go to the "My Devices" page.



On the "My Devices" page your plugs should appear here.

Select "Plugs"

Turning Plugs On or Off



By pressing the icon you can turn a plug on or off.



Orange is on

White is off

Data

- Household level hourly meter data
  - Sample: September 1, 2021 - June 30, 2023
  - Over 15 million observations
- Time-stamped App Interaction data
- For Central and Tech Programs: Device-specific hourly usage and opt-out information
- Weather data (temp, humidity)

Program Acceptance

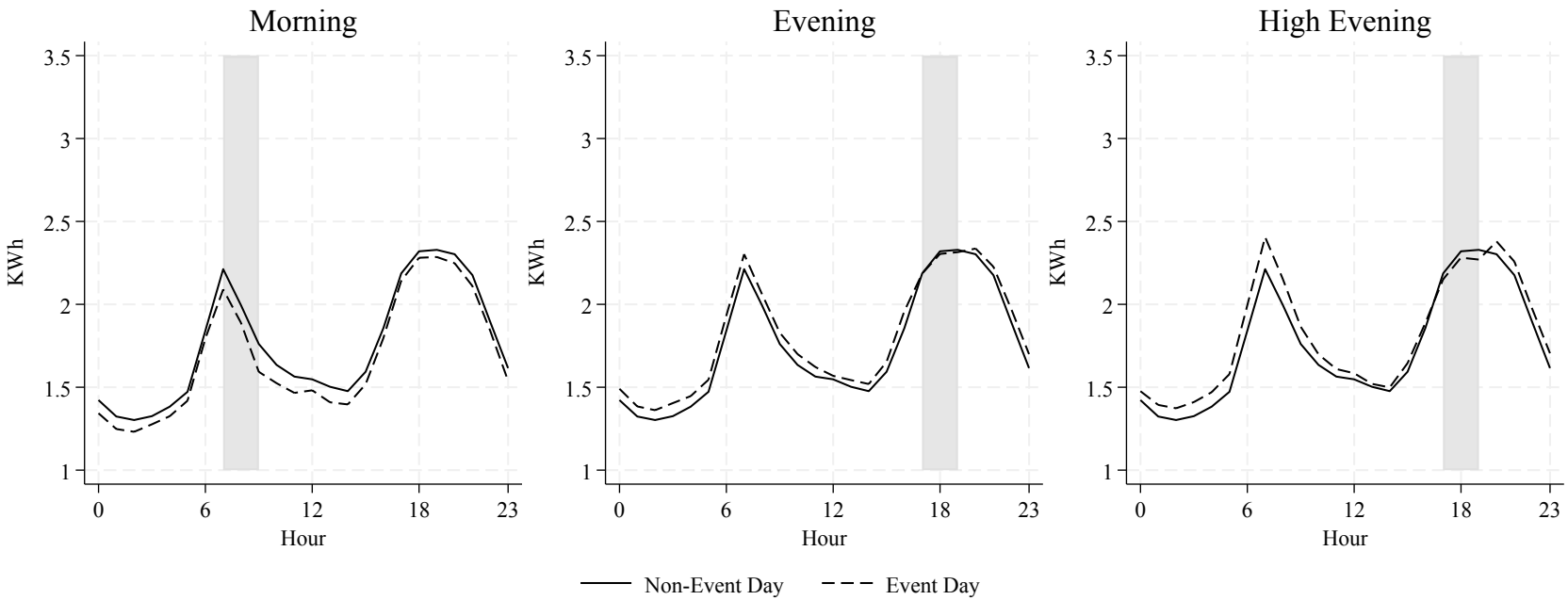
Acceptance Rates by Group

	Central	Tech	Manual	Control
Invited	423	382	409	188
Accepted	177	184	242	188
	(42%)	(48%)	(59%)	(100%)

Balance Table All HHs Balance Table Accepted HHs Installed Devices

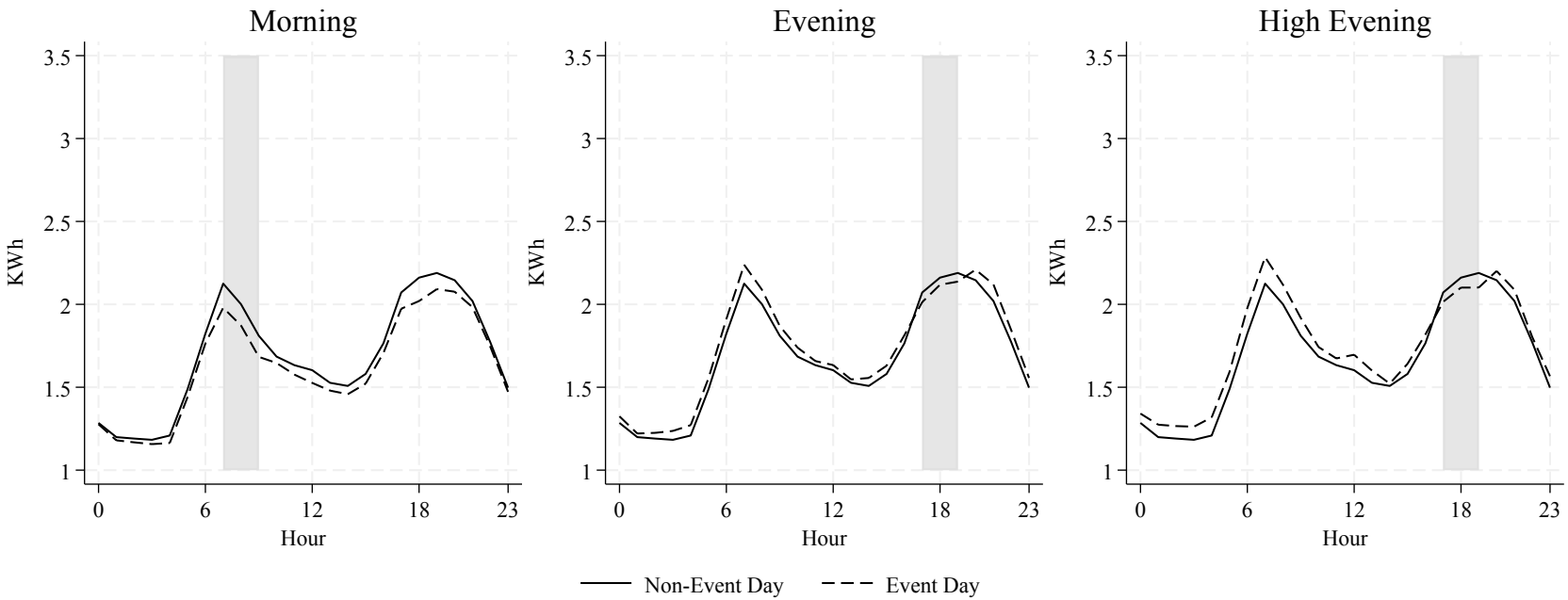
Descriptive Analysis

Manual Group: Non-event vs Event days



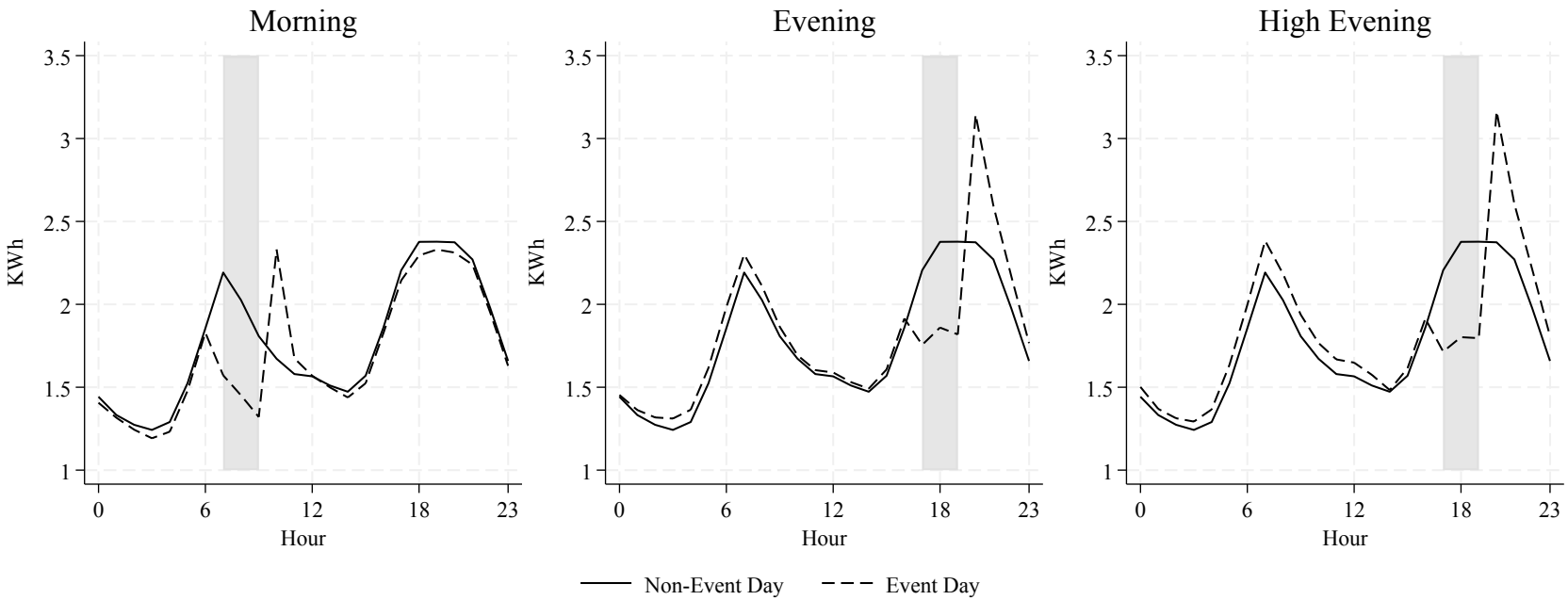
Descriptive Analysis

Tech Group: Non-event vs Event days



Descriptive Analysis

Central Group: Non-event vs Event days



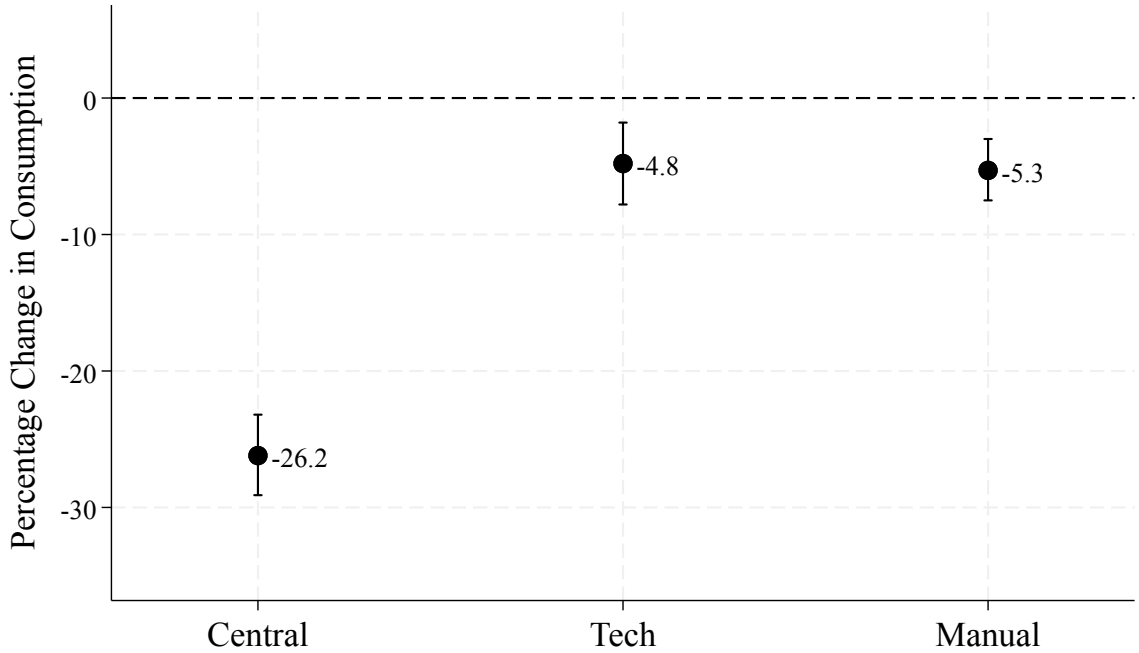
Estimation Strategy: Program-Level

Compare event times to non-event, controlling for household and time fixed effects, weather variables, and heterogeneity by program:

$$ln(c_{it}) = \sum_{j \in \{C,T,M\}} \left(\beta_j \, \text{Program}_{ji} \cdot E_{it} + \gamma_j \, \text{Program}_{ji} \cdot Spillover_{it} \right) + \alpha_i + \tau_t + \delta X_{it} + \varepsilon_{it}$$

- c_{it} is hourly household consumption
- Program_{ji} are program indicators (Central, Tech, Manual)
- E_{it} is an event indicator variable
- $Spillover_{it}$ two hours pre- and post-event indicators
- $\mathbf{X}_t$: Hourly weather variables (CDD, HDD, Humidity)
- Fixed effects at the household (α_i) and hour-of-sample (τ)
- Cluster SEs at HH-level

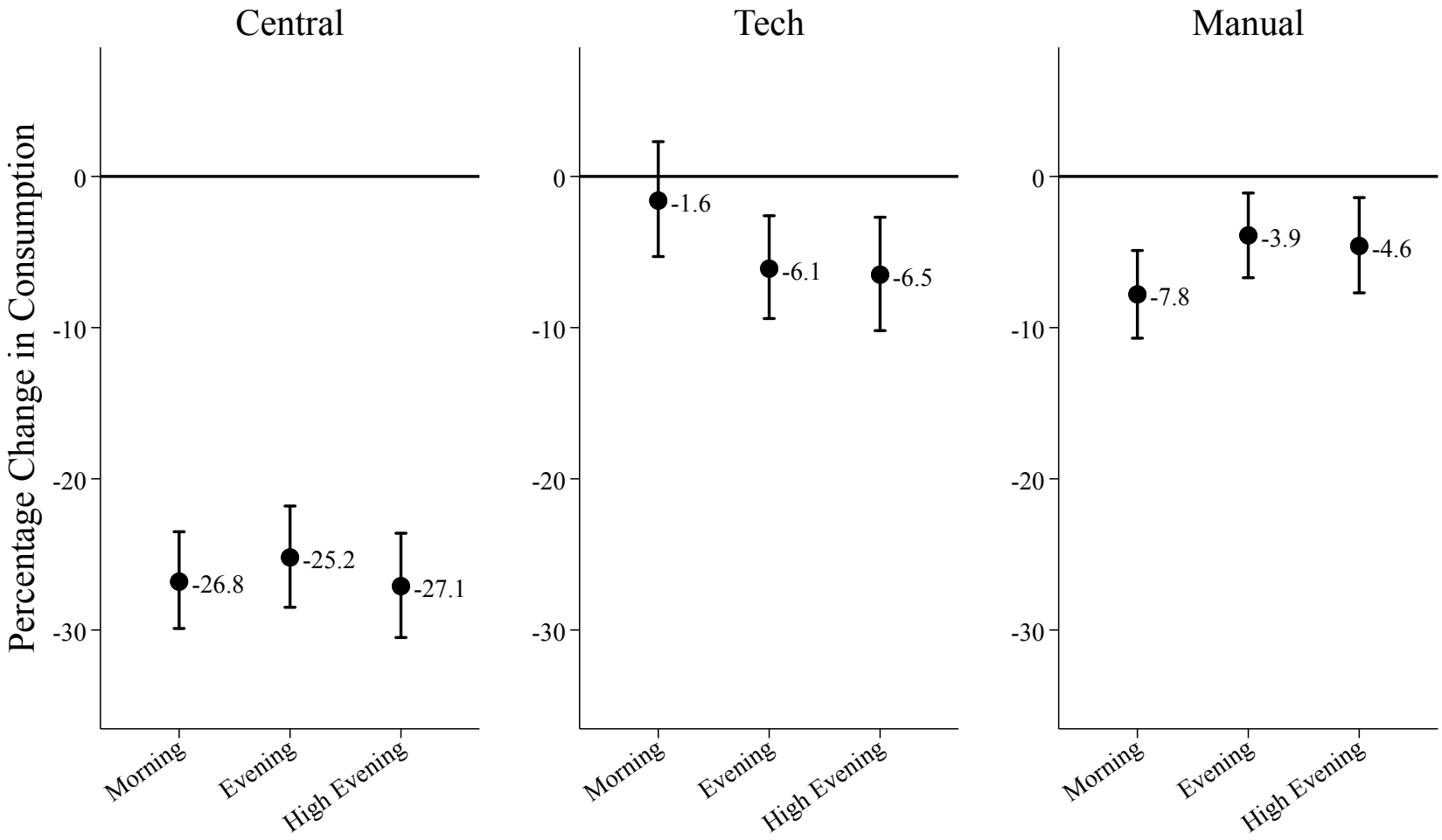
Results: Hourly Consumption Changes



- Central differs considerably from the Tech program
- Tech program not performing better than Manual
- Central program has minimal opt-out ($< 4\%$)

Spillover Controls | No Carry Over | Dynamic Effects | Comparison Robustness | ITT | Attrition | Bounds Analysis

Results: Hourly consumption changes by event type



- No significant differences as we elevate financial incentives
- Consistent with TOU experiment in Ireland (Prest, 2020)

Fixed Effect Robustness

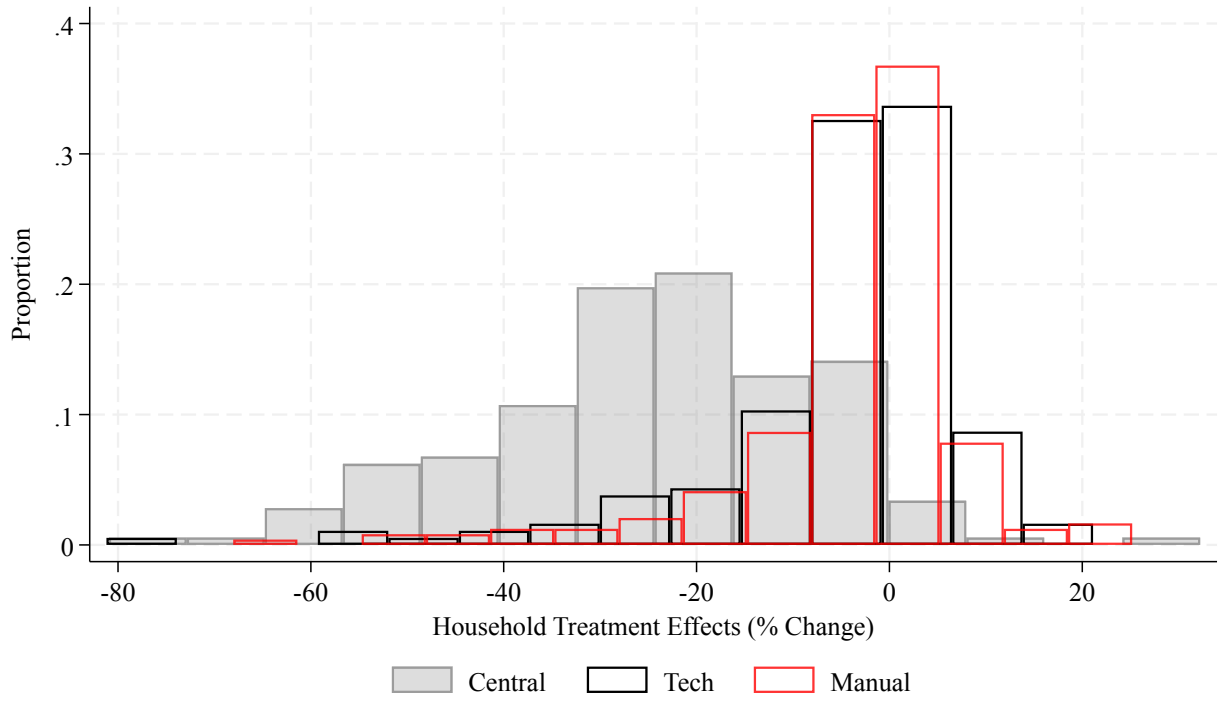
Estimation Strategy: Household-Level

Compare event times to non-event within a household controlling for time fixed effects and weather:

$$ln(c_{it}) = \mu_i + \beta_i E_{it} + \gamma_i Spillover_{it} + T_t + \delta_i X_{it} + \eta_{it}$$

- Time-series regression, leverages within-subject variation only
- $\widehat{\beta}_i$: household-specific treatment effects
- Estimate the full distribution of peak event responses

Household-Level Estimates



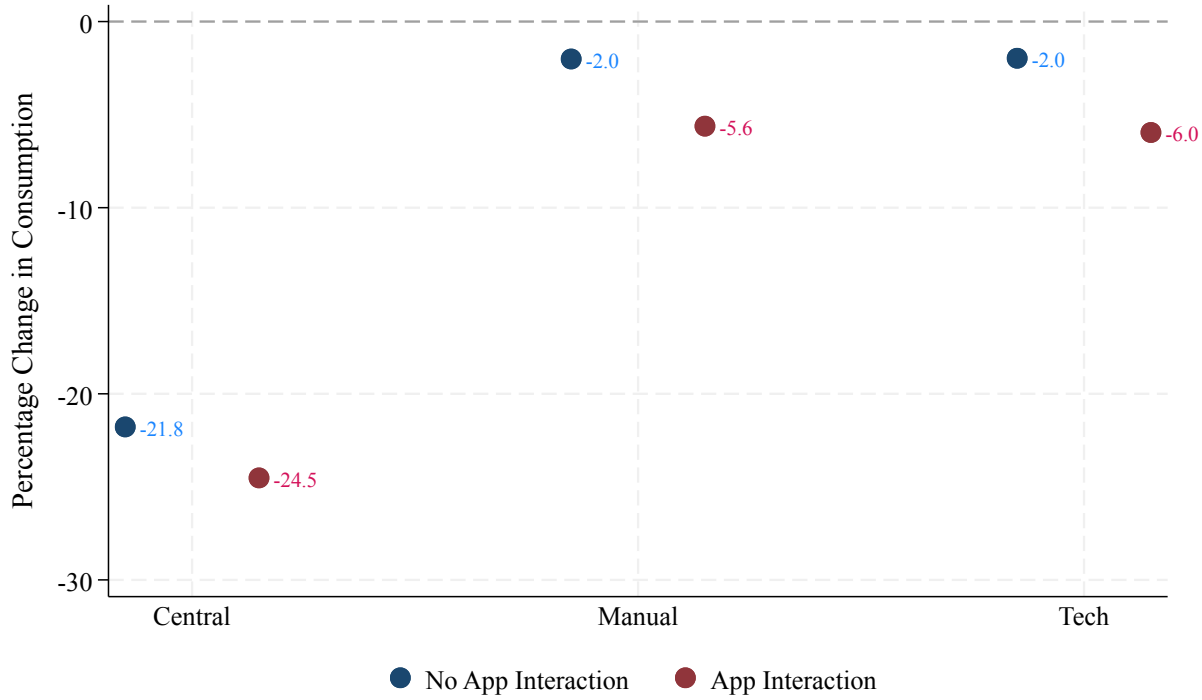
- Tech and Manual averages 4.6% and 4% ($\approx$ 20% significant)
  - Some outliers (large responders)
- Central average 24% ($\approx$ 80% significant)

Consistency of Response

Mechanisms: Time, Effort, and Attention

- What is driving the differences *between* and *within* demand response programs?
- Leverage household-level regression + App Interaction Data
- Question: *within* a household, do we see a differential response by whether or not they interact with the App?

App Interaction by Program



- Larger responses by App Interaction *within* HH
- Central group has a considerable "head start" regardless of App Interact

App Interaction: Detailed Decomposition

Use household-level estimates to segment households into performance quartiles (across all three DR programs)

Program	Performance Quartile	Household Count	General Interact	Devices Tab
Central	1	111 (63%)	0.32	0.18
	2	44 (25%)	0.19	0.12
	3	15 (8%)	0.21	0.15
	4	7 (4%)	0.15	0.11
Tech	1	20 (11%)	0.54	0.32
	2	43 (23%)	0.30	0.18
	3	53 (29%)	0.23	0.11
	4	68 (37%)	0.13	0.07
Manual	1	20 (8%)	0.59	0.07
	2	64 (26%)	0.18	0.03
	3	83 (34%)	0.15	0.03
	4	75 (31%)	0.14	0.02

Quartile Shares

Decomposing Responsiveness

Our estimated response = (Likelihood of Responding) $\times$
(Magnitude of Response | Responding)

Questions:

- Can we disentangle these two pieces, and see if they differ by program?
- Is it the higher likelihood of responding that gives Central the higher effect, larger conditional response, or a mix of both?

Step 1: Identifying Responders

Use HH-level estimates to find HHs with estimated treatment effects that are negative (i.e. reductions) with p-value < 0.05

- Captures "consistent" responders

Program	Count "Responders"	Participants in Program	Proportion of "Responders"
Manual	44	242	18%
Tech	37	184	20%
Central	142	177	80%

Step 2: Conditional Effect

Use the HH-level estimates and calculate the mean treatment effect of those flagged as responders

Program	Count "Responders"	Participants in Program	Proportion of "Responders"	Overall % Reduction
Manual	44	242	18%	-23%
Tech	37	184	20%	-27%
Central	142	177	80%	-31%

Central not only increases the likelihood of responding, it also increases the conditional magnitude of response

Responder Definition | Device-Specific Results | Exit Survey | External Validity

Summing up

We ran a large field experiment to explore the role of effort and technology in demand response

We find:

1. Take-up rates similar between Central and Tech (both lower than Manual)
2. Central group dominates in responsiveness (5x greater)
3. Tech group no better than Manual
4. App interactions are correlated with responsiveness, particularly key for Tech and Manual

Key takeaways:

1. Central boosts likelihood of responding (confirms attention and effort are key barriers)
2. Conditional on responding, Central program also performs better! (larger magnitude)

Conclusions & Policy Implications

- Suggest considerable role for automation with passive (default) responses
  - Importance of reducing effort costs when presenting consumers with repeated small stakes rewards ("picking up pennies")
  - Overcomes barrier of inattention
- Price-only incentives might leave flexibility on the table & potentially limited value of tech-only
  - Consistent with work on smart thermostats (Brandon et al., 2022)
- **Next question:** Willingness to hand over control?

Thank You!

dpbrown@ualberta.ca

Recruitment Details

- Population: Residential customers in and near a large metropolitan city
- Recruitment: emails, Utility website, social media, Utility newsletter, notification upon logging into Utility accounts
- Initial Sample: 9,020 households onto the Utility's App - filled out an initial survey
- Selection Criteria: 1,661 households to randomize
  - (i) Homeowners in single-family homes, duplexes, or row homes
  - (ii) At least one month of consumption data as of Sept. 2021
  - (iii) At least one potentially controllable device (Hot Water, EV Level 2, Baseboard Heaters)

Back

Load-Control Devices





Installed on hot water heaters, thermostats/baseboard heating, level 2 electric vehicle chargers

Back

Balance by Group - All Households

Table: Comparison of Means by Program - Initial Randomization

	Central	Tech	Manual	Info	Control	ANOVA (p-value)
Cumul. KWhs						
Winter	5,279	5,268	5,442	4,859	5,265	0.27
	(2,694)	(3,032)	(3,076)	(2,748)	(2,950)	
Spring	3,760	3,773	3,818	3,503	3,712	0.48
	(1,924)	(2,112)	(1,911)	(2,116)	(1,974)	
Summer	2,845	2,836	2,708	2,614	2,729	0.54
	(1,742)	(1,872)	(1,539)	(1,861)	(1,710)	
Fall	3,633	3,670	3,700	3,458	3,623	0.66
	(1,663)	(1,945)	(1,974)	(1,796)	(1,860)	
Load Factor						
Winter	24.66	24.98	25.41	24.73	24.67	0.81
	(8.20)	(8.15)	(8.80)	(8.29)	(8.63)	
Spring	19.52	20.12	20.01	19.28	19.91	0.65
	(7.25)	(6.97)	(6.70)	(7.73)	(7.41)	
Summer	16.82	16.55	16.73	16.12	16.32	0.82
	(7.89)	(6.30)	(5.93)	(8.11)	(8.29)	
Fall	18.56	18.90	19.34	18.42	19.06	0.42
	(5.89)	(6.23)	(6.00)	(6.48)	(6.50)	
Electric Vehicle	0.27	0.27	0.27	0.33	0.27	0.41
	(0.44)	(0.45)	(0.45)	(0.47)	(0.45)	
Baseboard Heating	0.61	0.64	0.61	0.63	0.63	0.95
	(0.49)	(0.48)	(0.49)	(0.48)	(0.48)	
Air Conditioning	0.52	0.51	0.50	0.51	0.54	0.95
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)	
Electric Hot Water	0.70	0.66	0.70	0.66	0.72	0.38
	(0.46)	(0.47)	(0.46)	(0.47)	(0.45)	
House/Duplex	0.77	0.76	0.81	0.78	0.84	0.17
	(0.42)	(0.43)	(0.39)	(0.42)	(0.37)	
Median Income	86,376	88,291	85,931	87,470	85,948	0.48
	(19,503)	(22,227)	(19,255)	(21,574)	(21,541)	

Back

Comparison of Means by Program - Accepted Households

Table: Comparison of Means by Group - Final Accepted Households

	Central	Tech	Manual	Info	Control	ANOVA (p-value)
Cumul. KWhs						
Winter	5,507	5,302	5,422	5,037	5,265	0.71
	(2,706)	(2,737)	(3,240)	(2,768)	(2,950)	
Spring	3,900	3,739	3,797	3,642	3,712	0.85
	(1,934)	(1,791)	(1,939)	(2,159)	(1,974)	
Summer	2,851	2,672	2,766	2,702	2,729	0.93
	(1,869)	(1,759)	(1,547)	(1,849)	(1,710)	
Fall	3,754	3,550	3,677	3,547	3,623	0.86
	(1,733)	(1,659)	(1,992)	(1,788)	(1,860)	
Load Factor						
Winter	24.62	25.56	24.93	24.93	24.67	0.90
	(8.68)	(8.21)	(9.04)	(7.76)	(8.63)	
Spring	19.33	20.48	19.80	19.59	19.91	0.72
	(7.43)	(6.30)	(6.45)	(7.05)	(7.41)	
Summer	16.33	16.87	16.95	16.61	16.32	0.91
	(8.54)	(6.02)	(5.95)	(7.80)	(8.29)	
Fall	18.17	18.97	19.11	18.53	19.06	0.65
	6.27	5.78	6.29	6.11	6.50	
Electric Vehicle	0.25	0.21	0.30	0.34	0.27	0.07*
	(0.43)	(0.41)	(0.46)	(0.47)	(0.45)	
Baseboard Heating	0.68	0.70	0.60	0.59	0.63	0.12
	(0.47)	(0.46)	(0.49)	(0.49)	(0.48)	
Air Conditioning	0.46	0.46	0.51	0.51	0.54	0.41
	(0.50)	(0.50)	(0.50)	(0.50)	(0.50)	
Electric Hot Water	0.75	0.74	0.68	0.65	0.72	0.16
	(0.43)	(0.44)	(0.47)	(0.48)	(0.45)	
House/Duplex	0.82	0.77	0.89	0.84	0.84	0.02**
	(0.39)	(0.42)	(0.32)	(0.37)	(0.37)	
Median Income	84,978	88,274	86,718	89,504	85,948	0.23
	(19,647)	(20,432)	(19,494)	(21,079)	(21,541)	

Back

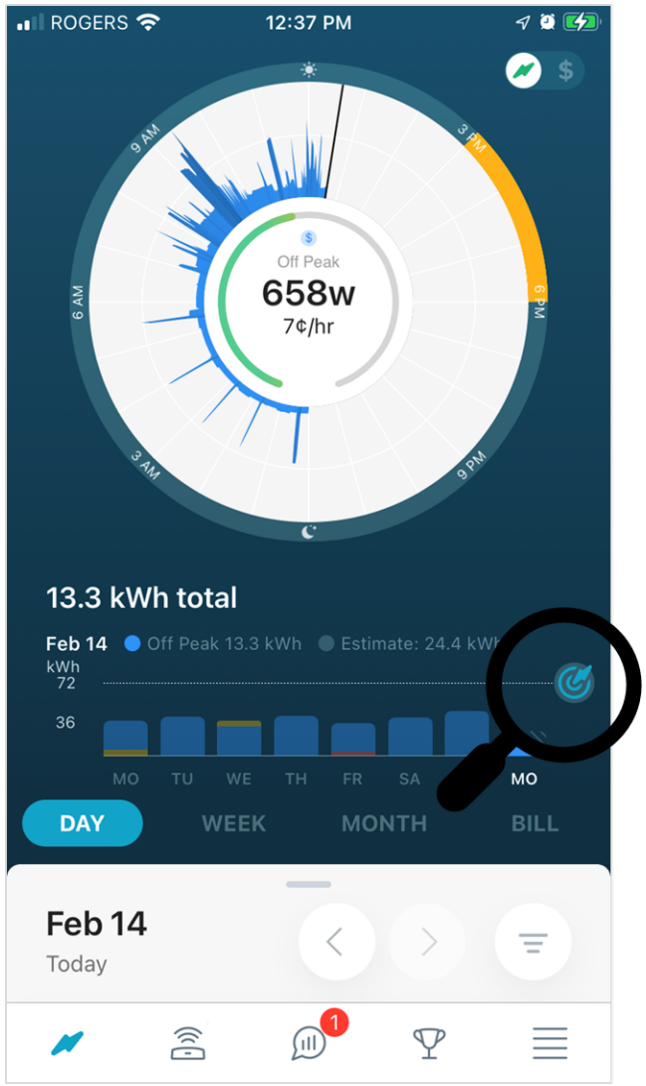
Installed Devices

Table C21. Installed Load Controllable Device Counts - Central and Tech Programs

	Households (Count)	Thermostats (Binary)	Thermostat (Count)	Water Heaters	EV
Central	177	112	469	127	23
Tech	184	116	468	132	16

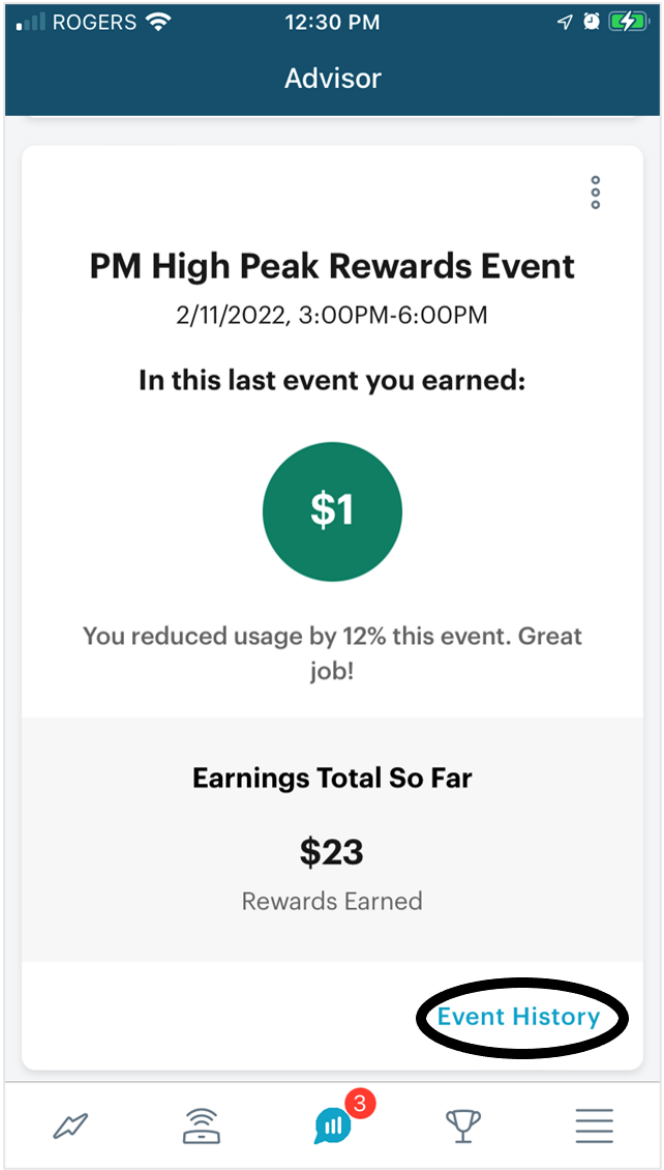
Back

User Experience: Real-Time Information



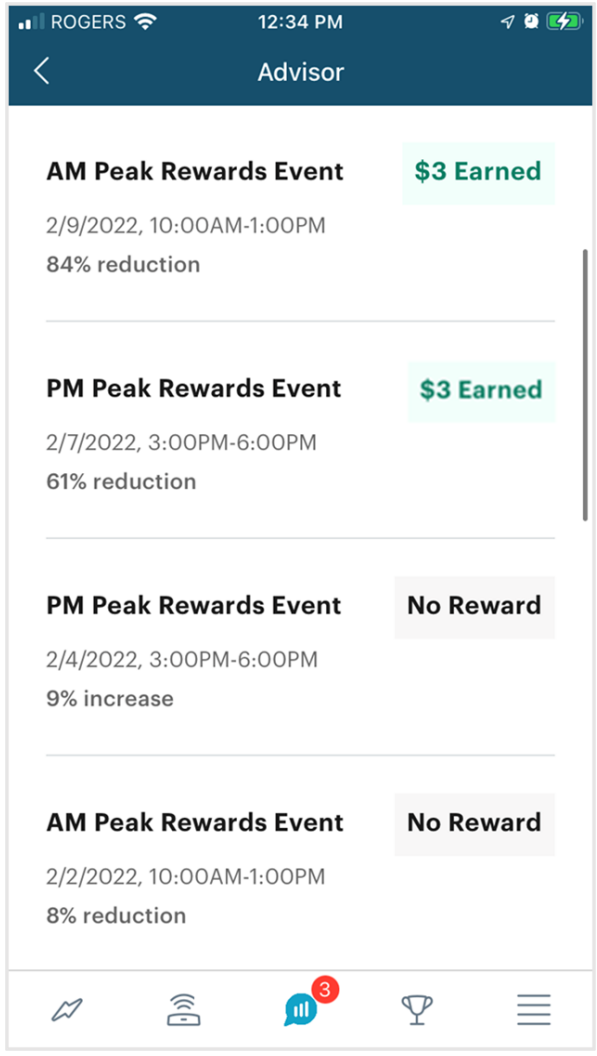
Back

Post-Event Feedback



Back

Post-Event Feedback



Back

Identification Strategy

- Framework: "Panel Experiments" or "within-subject" design (Bojinov et al., 2021; List, 2025)
- Identifying off of "between subject" and "within subject" variation
- Identifying variation: compares event time consumption to non-event time consumption of households (in same program, other programs, never-treated)
- Key Assumptions:
  1. Balanced Panel (Attrition)
  2. Causal Transience (No "Carry Over")
  3. Temporal Stability

Back

Identification Strategy

- Estimator: Average treatment effect to peak events by program for households that accepted the DR program offers

- Other typical estimators: ITT of DR program
  - Those that did not enroll in DR programs did not receive (randomized) peak events
  - Noisy null responses to (unobserved) peak events
  - ITT = main estimated effect $\times$ share of households that joined the program

Back

Comparison Group Robustness

Table C10. Treatment Effects of Participants by Program

Program	(1)	(2)	(3)	(4)	(5)
Central	-0.3151	-0.297	-0.3100	-0.2997	-0.3036
	(0.0206)	(0.0202)	(0.0206)	(0.0204)	(0.0204)
Tech	-0.0661	-0.0457	-0.0584	-0.0474	-0.0496
	(0.0132)	(0.0147)	(0.0152)	(0.0155)	(0.0160)
Manual	-0.0507	-0.0418	-0.0528	-0.0459	-0.0542
	(0.0092)	(0.0108)	(0.0113)	(0.0117)	(0.0123)
Comparisons					
Own Program	Y	Y	Y	Y	Y
Other Treated					Y
Never Treated-Control		Y		Y	Y
Never Treated-Info			Y	Y	Y

Back

Comparison Group Robustness

Table C11. Treatment Effects of Participants by Program and Event-Type

Program	(1)	(2)	(3)	(4)	(5)
Central					
Morning	-0.3198	-0.3138	-0.3186	-0.315	-0.3122
	(0.0221)	(0.0223)	(0.0227)	(0.0224)	(0.0223)
Evening	-0.3040	-0.2806	-0.2971	-0.2840	-0.2905
	(0.0218)	(0.0219)	(0.0229)	(0.0226)	(0.0228)
High Evening	-0.3291	-0.3057	-0.3228	-0.3095	-0.3166
	(0.0237)	(0.0237)	(0.0244)	(0.0241)	(0.0243)
Tech					
Morning	-0.0495	-0.0299	-0.0357	-0.0272	-0.0159
	(0.0128)	(0.0173)	(0.0176)	(0.0188)	(0.0199)
Evening	-0.0713	-0.0506	-0.0665	-0.0544	-0.0625
	(0.0155)	(0.0170)	(0.0181)	(0.0181)	(0.0185)
High Evening	-0.0786	-0.0569	-0.0727	-0.0603	-0.0677
	(0.0166)	(0.0188)	(0.0197)	(0.0200)	(0.0206)
Manual					
Morning	-0.0488	-0.0614	-0.0651	-0.0689	-0.0815
	(0.0097)	(0.0136)	(0.0140)	(0.0150)	(0.0159)
Evening	-0.0488	-0.0304	-0.0446	-0.0331	-0.0399
	(0.0108)	(0.0129)	(0.0139)	(0.0143)	(0.0149)
High Evening	-0.0567	-0.0377	-0.0519	-0.0402	-0.0470
	(0.0126)	(0.0147)	(0.0155)	(0.0159)	(0.0166)
Comparisons					
Own Program	Y	Y	Y	Y	Y
Other Treated					Y
Never Treated-Control		Y		Y	Y
Never Treated-Info			Y	Y	Y

Back

Attrition Robustness

Table C5. Enrolled Participants by Program and Month

Year	Month	Central	Tech	Manual	Info	Control
2022	1	177	184	242	177	188
2022	2	177	184	242	175	188
2022	3	177	184	242	175	188
2022	4	177	184	242	173	188
2022	5	176	184	241	172	188
2022	6	175	184	241	171	187
2022	7	173	184	238	170	185
2022	8	172	182	237	168	184
2022	9	171	182	237	168	180
2022	10	170	181	237	168	178
2022	11	169	180	237	168	177
2022	12	169	179	236	167	177
2023	1	169	179	235	167	177
2023	2	168	178	234	167	177
2023	3	166	177	233	166	176
2023	4	166	177	231	166	176
2023	5	166	177	231	165	175
2023	6	166	175	231	165	175
Final Attrition (%)		6.21	4.89	4.55	6.78	6.91

Notes. This table reports the count of households that were enrolled by program. Final attrition (%) represents the percentage of initially enrolled users that unenrolled by the end of our experiment (June 2023).

Back

Attrition Robustness

Table C6. Program-Level Estimates by Program and Phase with Full and Balanced Samples

	(1) Full	(2) Phase 1	(3) Phase 2	(4) Phase 3	(5) Balanced	(6) Phase 1	(7) Phase 2	(8) Phase 3
Central	-0.3036	-0.3608	-0.2824	-0.2717	-0.3042	-0.3646	-0.2823	-0.2730
	(0.0204)	(0.0242)	(0.0212)	(0.0247)	(0.0208)	(0.0250)	(0.0216)	(0.0248)
Tech	-0.0496	-0.0656	-0.0398	-0.0453	-0.0536	-0.0731	-0.0432	-0.047
	(0.016)	(0.0184)	(0.019)	(0.0194)	(0.0161)	(0.019)	(0.0191)	(0.0194)
Manual	-0.0542	-0.0783	-0.0484	-0.0377	-0.0538	-0.0765	-0.0494	-0.0376
	(0.0123)	(0.0154)	(0.0139)	(0.0157)	(0.0124)	(0.0158)	(0.014)	(0.0158)

Notes. The reported results are program-specific treatment effect coefficients using the specification in Equation (1). Standard errors are reported in the parentheses and clustered at the household level. Columns (1) and (5) report the regression results for the Full and Balanced samples for all months. Columns (2) - (4) and (6) - (8) report the regression results including the Full and Balanced samples across Phases 1, 2, and 3, respectively. All specifications include fixed effects at the household and hour-of-sample levels. Standard errors are clustered at the household-level.

Back

Bounds Analysis

- Concern of differential sample selection across programs driving differential in responses across programs
- Question: Is the large wedge between Central and Tech/Manual due to the fact that a subset of (unique) HHs joined the latter programs, but not the former?
- Bounds Analysis: Assume the additional proportion of HHs offered Central joined to make the acceptance rates equal to Manual/Tech, but impose a 0 response

Back

Bounds Analysis

Table C9. Lower Bound Program-Level Average Treatment Effects for Central and Tech (Percentage Change in Peak Event Demand)

	Central	Tech
Tech-Adjusted	-23.18	–
Manual-Adjusted	-19.32	-3.96

Notes. The reported results reflect our average estimated treatment effects of program participants in Equation (1), adjusted downward using our lower-bounding exercise detailed in Equation (6). A lower bound exercise is implemented for Central, relative to the higher Tech and Manual acceptance rates, while a lower bound calculation is only done for Tech relative to Manual. The lower bound estimates are translated into percentage change as follows: $100 \times (\exp(\underline{DR}_{j,k}) - 1)$.

Back

No Carry Over

For each demand response program, we run separate regressions:

$$ln(c_{it}) = \beta D_i \cdot \text{EventWindow}_{it} + \alpha_i + \tau_t + \delta X_{it} + \varepsilon_{it} \quad (1)$$

- Excludes event days
- Includes never-treated HHs
- EventWindow_{it} equals 1 in the post-treatment period for hours where morning or evening events occur, 0 otherwise
- D_i equals 1 if the household is in a demand-response group (i.e., C, T, or M), 0 otherwise

Back

No Carry Over: Results

Table C3. Carry Over DID Estimates by Program

	Central	Tech	Manual
Event Window	0.0241	0.0302	-0.0014
	(0.0169)	(0.0181)	(0.0155)

Back

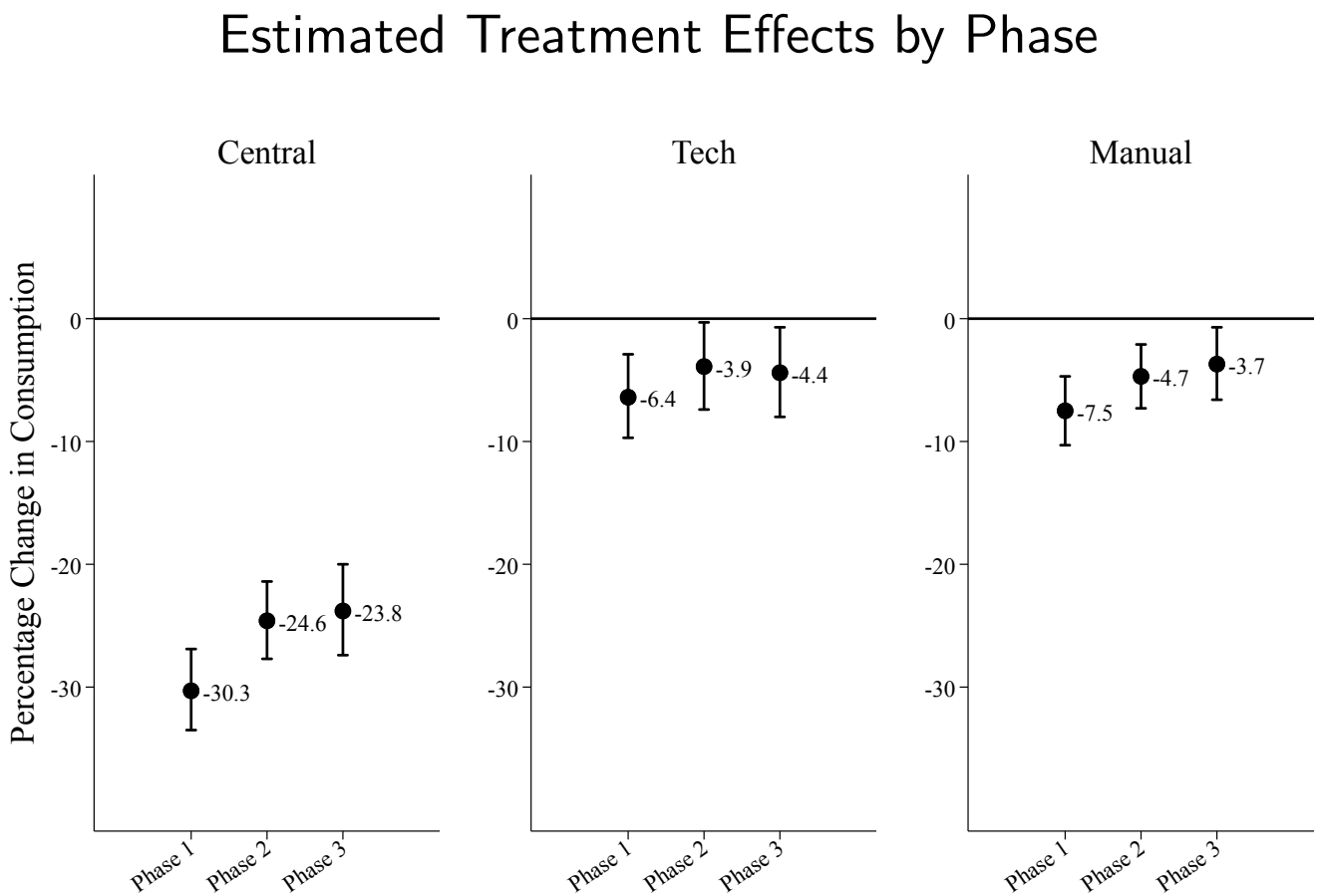
No Carry Over: Results

Table C4. Carry Over DID Estimates by Program and Event Type

	Central	Tech	Manual
Morning Event Window	0.0188	0.0353	-0.0226
	(0.0206)	(0.0235)	(0.0201)
Evening Event Window	0.0295	0.0251	0.0196
	(0.0212)	(0.0210)	(0.0185)

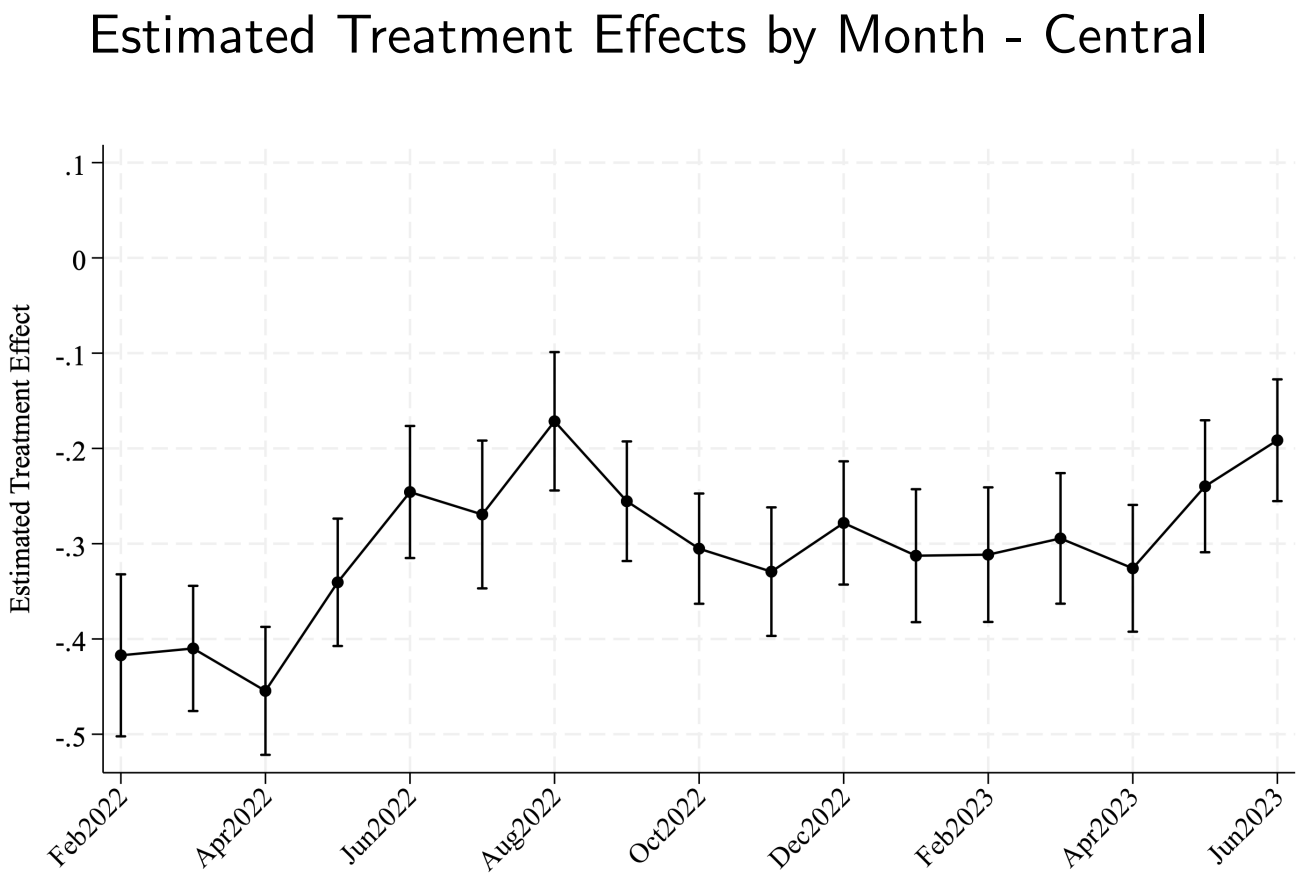
Back

Dynamic Treatment Effects



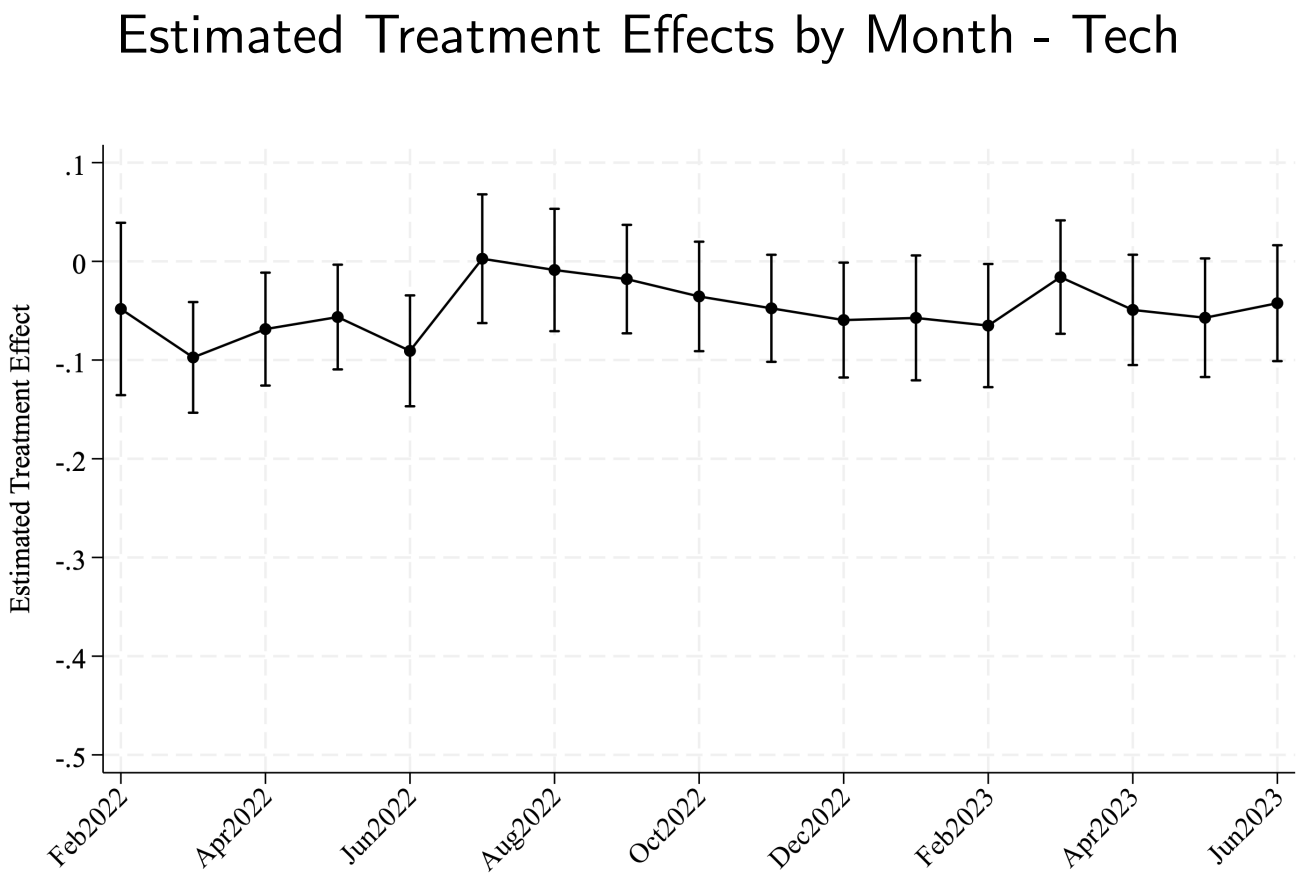
Back

Dynamic Treatment Effects - Central



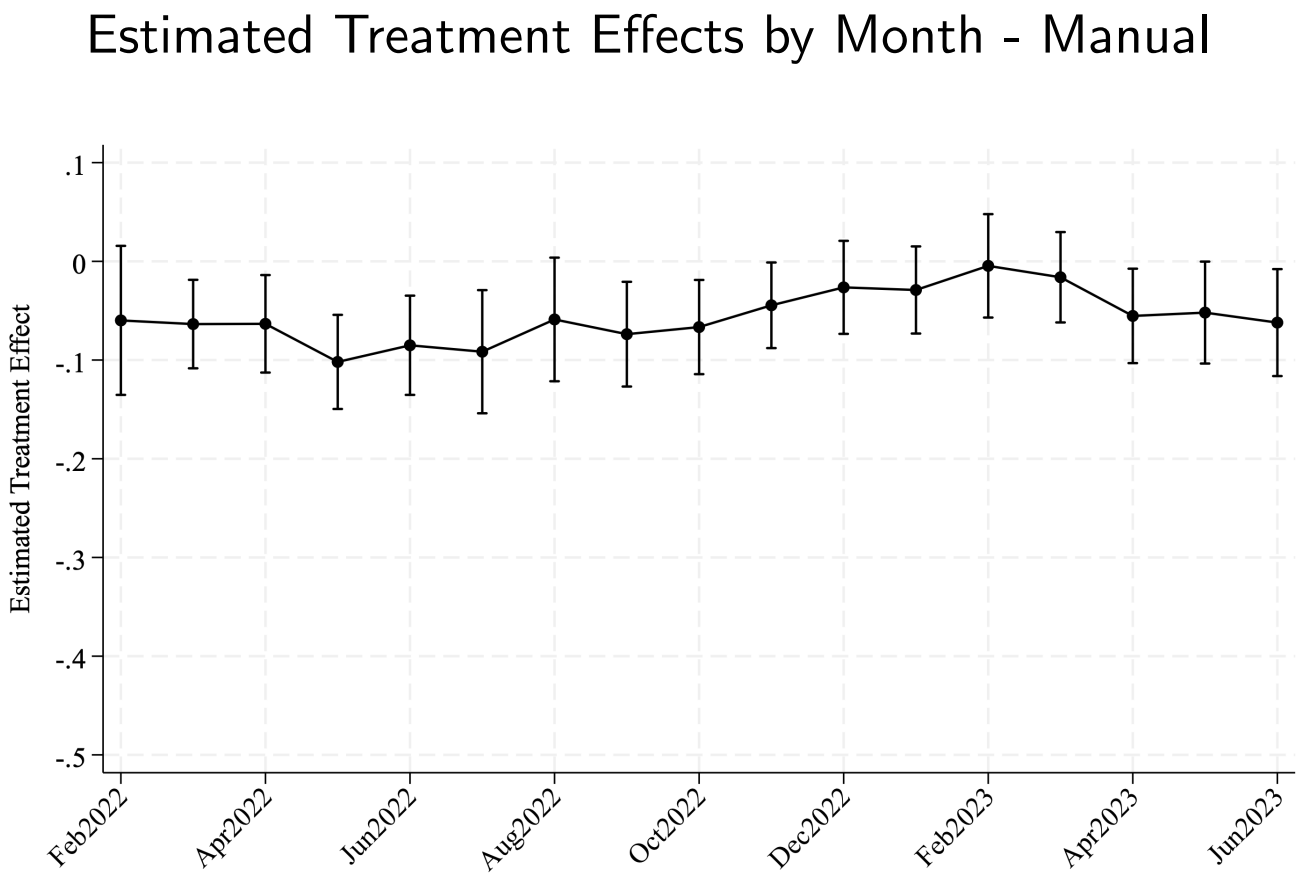
Back

Dynamic Treatment Effects - Tech



Back

Dynamic Treatment Effects - Manual



Back

Controlling for Spillover Effects

Table C3. Treatment Effects of Participants by Program - Spillover Effects

Program	Pre-Event	Event	Post-Event
Central	0.0056	-0.3036***	0.2063***
	(0.0123)	(0.0204)	(0.0195)
Tech	0.0163	-0.0496***	0.0034
	(0.0118)	(0.0160)	(0.0121)
Manual	0.0030	-0.0542***	-0.0031
	(0.0102)	(0.0123)	(0.0101)

Notes. The reported results are program-specific treatment effect coefficients in (1), with the addition of demand response group-specific Pre-Event and Post-Event covariates. Pre-Event (Post-Event) is an indicator that equals 1 for two hours prior to (after) peak events, and zero otherwise. Standard errors are reported in the parentheses and clustered at the household level. All specifications include fixed effects at the household and hour-of-sample levels. Statistical Significance * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Back

ITT-like: Approach

- Full sample (accept/non-accept)
- Non-acceptors - allocate from same distribution of peak events ("synthetic events")
- Rerun main specification, but for non-acceptors replace "realized event" with synthetic events as an "Assigned Event"

Back

ITT-like: Results

Table C7. ITT Estimates by Program

	Central	Tech	Manual
Assigned × Event	-0.1475	-0.0376	-0.0286
	(0.0139)	(0.0102)	(0.0089)

Notes. The reported results are program-specific ITT coefficients from equation (5). For each demand response program, the sample includes households from their own treatment program and the never-treated groups. Standard errors are reported in the parentheses and clustered at the household level. All specifications include fixed effects at the household and hour-of-sample levels.

Back

Fixed Effect Robustness

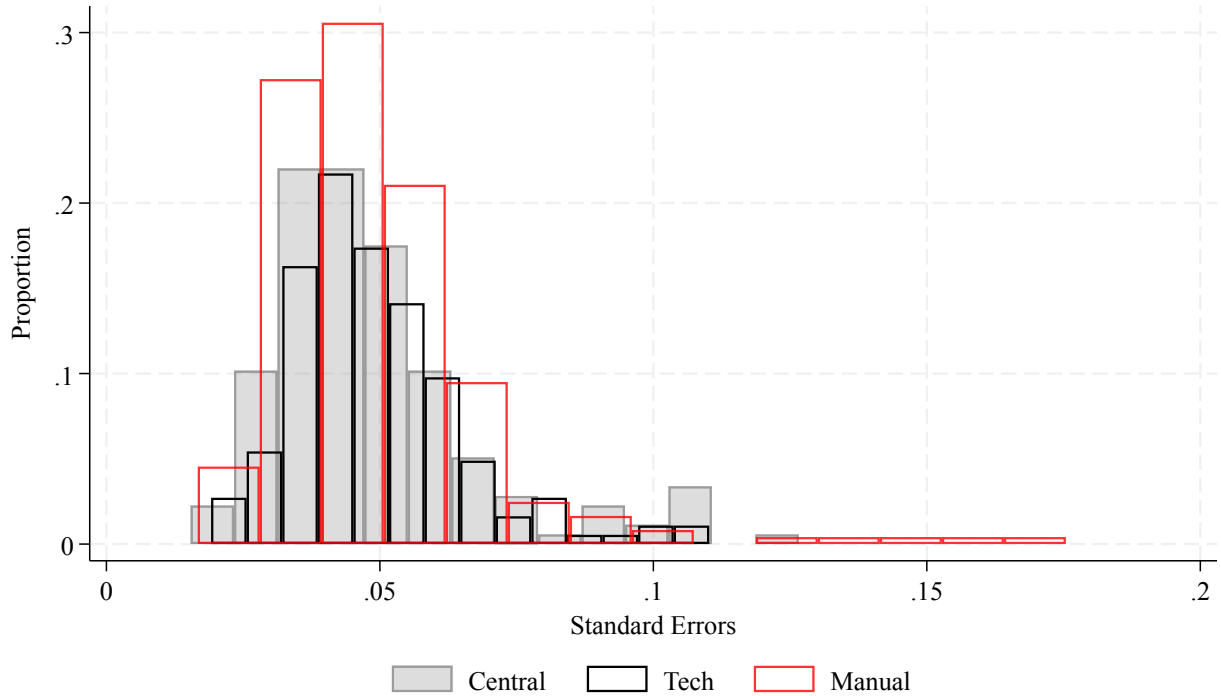
Table C17. Treatment Effects of Participants by Program and Event-Type - Fixed Effects Robustness

Program	(1)	(2)	(3)	(4)	(5)
Central					
Morning	-0.2974	-0.3122	-0.3253	-0.3119	-0.3131
	(0.0220)	(0.0223)	(0.0220)	(0.0222)	(0.0221)
Evening	-0.2896	-0.2905	-0.3069	-0.2893	-0.2944
	(0.0225)	(0.0228)	(0.0215)	(0.0231)	(0.0221)
High Evening	-0.3145	-0.3166	-0.3329	-0.3144	-0.3144
	(0.0242)	(0.0243)	(0.0236)	(0.0245)	(0.0233)
Tech					
Morning	0.0030	-0.0159	-0.0457	-0.0176	-0.0130
	(0.0201)	(0.0199)	(0.0151)	(0.0197)	(0.0200)
Evening	-0.0653	-0.0625	-0.0697	-0.0641	-0.0628
	(0.0187)	(0.0185)	(0.0167)	(0.0187)	(0.0181)
High Evening	-0.0640	-0.0677	-0.0754	-0.0702	-0.0636
	(0.0203)	(0.0206)	(0.0177)	(0.0207)	(0.0200)
Manual					
Morning	-0.0668	-0.0815	-0.0559	-0.0806	-0.0809
	(0.0158)	(0.0159)	(0.0114)	(0.0158)	(0.0160)
Evening	-0.0409	-0.0399	-0.0472	-0.0403	-0.0426
	(0.0150)	(0.0149)	(0.0112)	(0.0150)	(0.0146)
High Evening	-0.0424	-0.0470	-0.0546	-0.0467	-0.0497
	(0.0170)	(0.0166)	(0.0132)	(0.0166)	(0.0166)
Fixed Effects					
Household	Y	Y			
Year-Month	Y				
Day-of-Week	Y				
Hour-of-Day	Y				
Hour-of-Sample		Y	Y	Y	Y
Household-Hour-of-Day			Y		
Household-Day-of-Week				Y	
Household-Year-Month					Y

Notes. The reported results are program-specific treatment effect coefficients by event type. Standard errors are reported in the parentheses and clustered at the household level. Columns (1) - (5) vary the fixed effects included in the analysis indicated in the bottom panel of the Table.

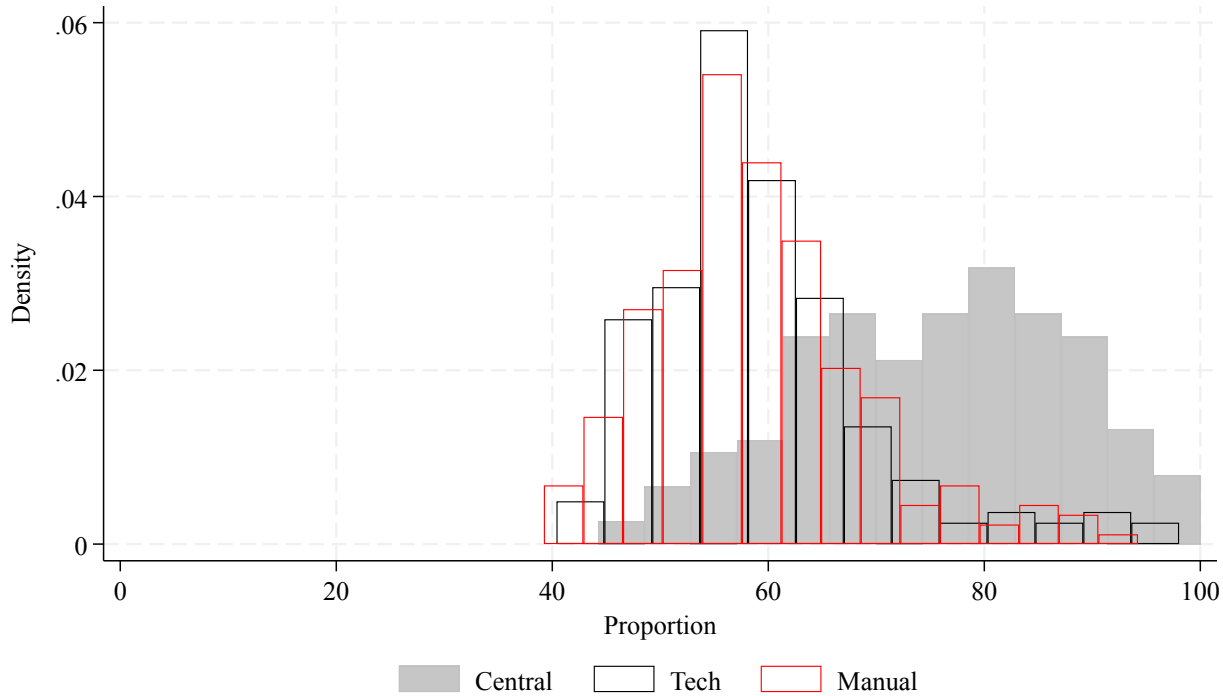
Back

Consistency of Household-Level Estimates



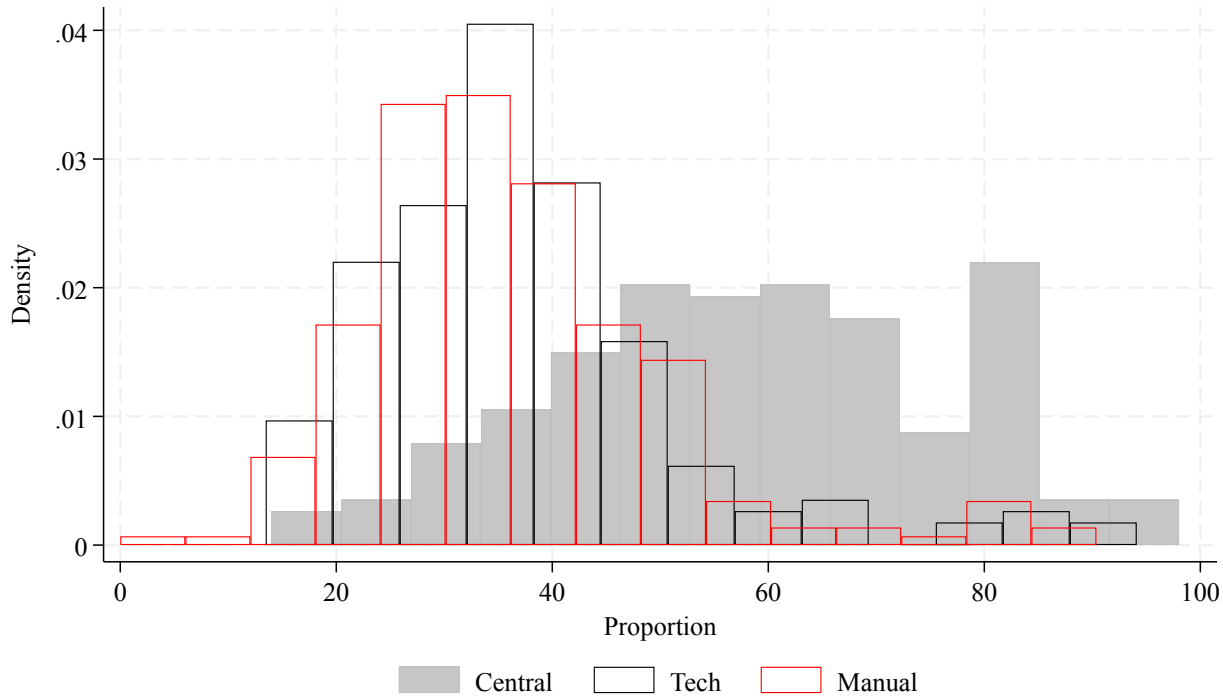
Back

Consistency of Household-Level Estimates: 0% Response



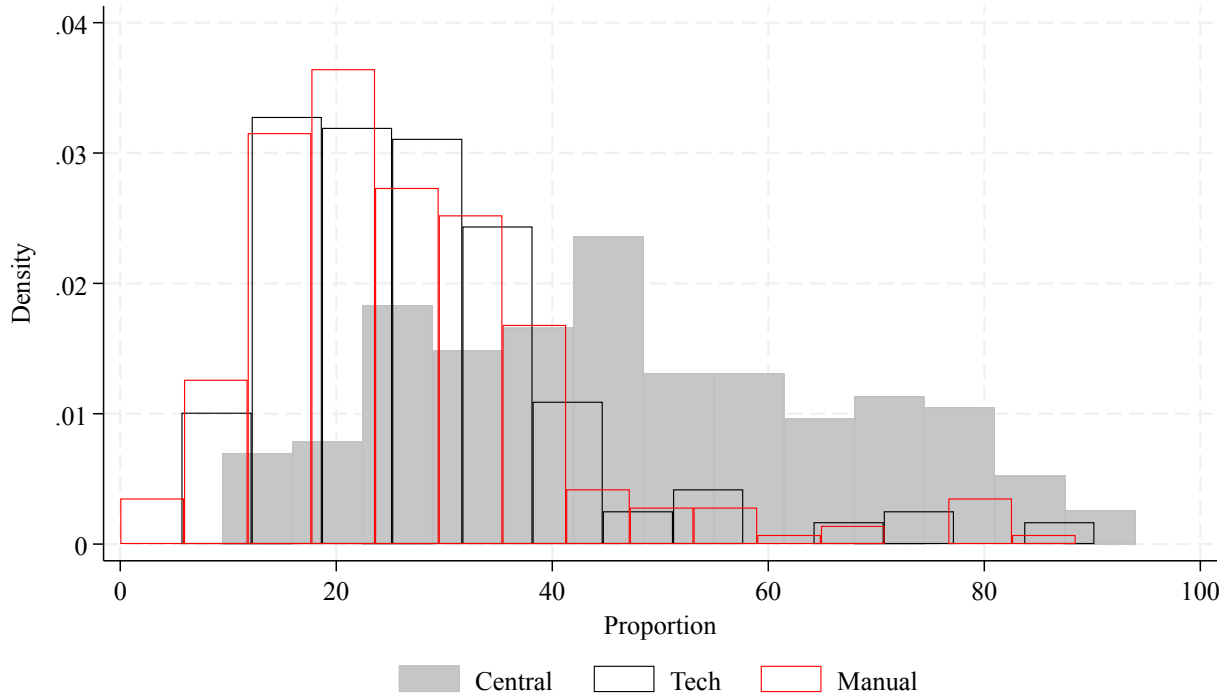
Back

Consistency of Household-Level Estimates: 20% Response



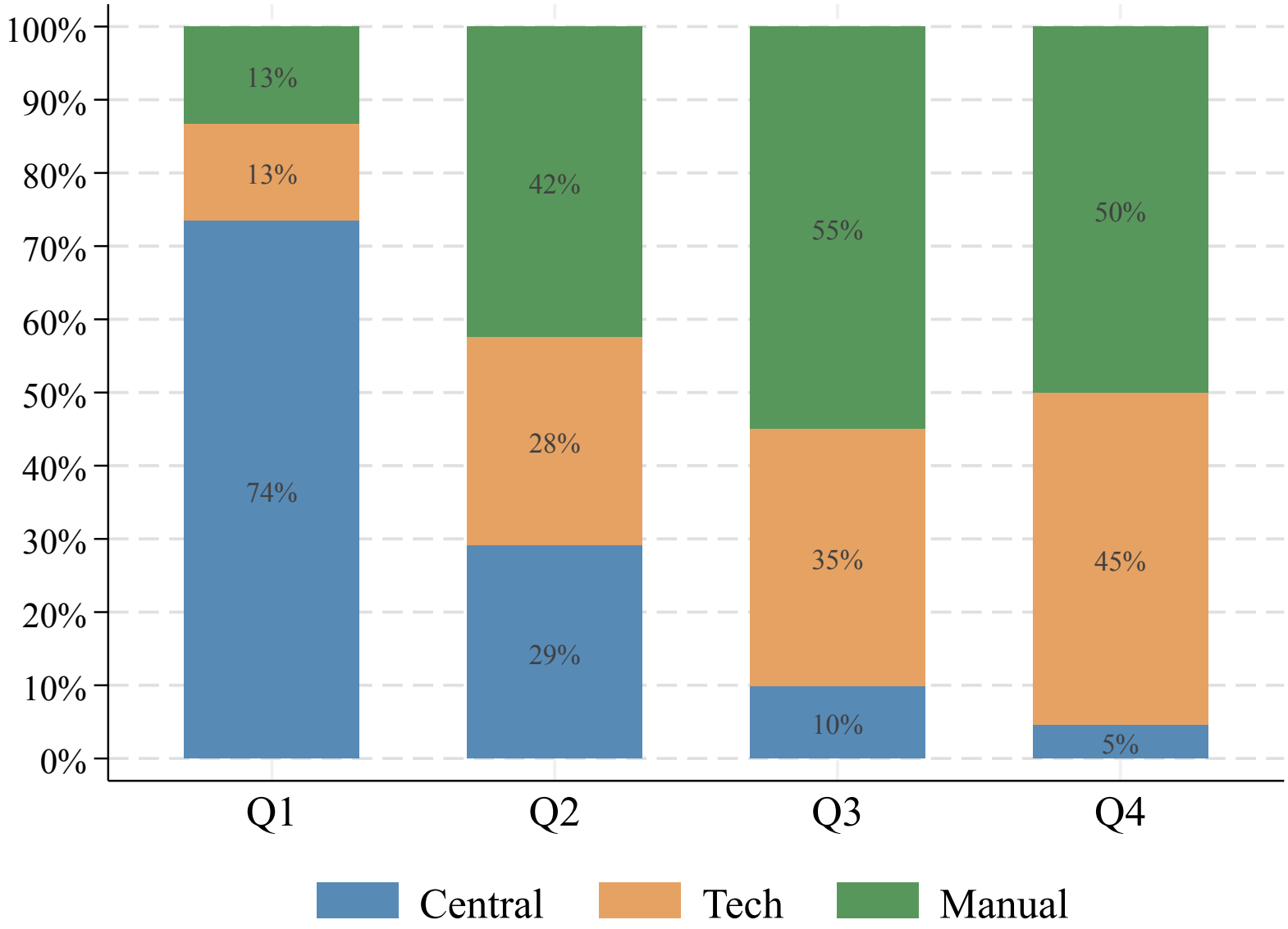
Back

Consistency of Household-Level Estimates: 30% Response



Back

Share of Participants by Performance Quartile



Back

Responder Definition Robustness

Table C19. Responder Shares and Average Peak Demand Reduction Among Responders - P-Value Robustness

	Central	Tech	Manual
p = 0.01			
Share of Responders	0.76	0.15	0.13
Household Treatment Effect (%)	-32.13	-31.18	-26.94
p = 0.025			
Share of Responders	0.79	0.17	0.15
Household Treatment Effect (%)	-31.67	-28.94	-24.9
p = 0.05			
Share of Responders	0.80	0.20	0.18
Household Treatment Effect (%)	-31.29	-27.11	-22.93
p = 0.075			
Share of Responders	0.83	0.22	0.21
Household Treatment Effect (%)	-30.65	-25.46	-21.19
p = 0.10			
Share of Responders	0.84	0.26	0.24
Household Treatment Effect (%)	-30.36	-22.83	-19.53

Notes. The reported results present the average household-level estimated treatment effects from estimating specification (2), focusing only on households deemed to be responders. We vary the definition of responders whose coefficients are negative and significant at the p-value 0.01, 0.025, 0.05, 0.075, and 0.10 levels. We present the marginal effects to be a percentage change in consumption using the transformation $100 \times (exp(\widehat{\beta}_i) - 1)$. Share of responders represents the percentage of households within a demand response program that are classified as responders.

Back

Responder Definition Robustness

Table C20. Responder Shares and Average Peak Demand Reduction Among Responders - % Reduction Threshold

	Central	Tech	Manual
Reduction 2.5%			
Share of Responders	0.93	0.47	0.45
Household Treatment Effect (%)	-28.4	-15.35	-13.46
Reduction 5%			
Share of Responders	0.87	0.34	0.34
Household Treatment Effect (%)	-29.75	-19.2	-16.21
Reduction 7.5%			
Share of Responders	0.82	0.24	0.24
Household Treatment Effect (%)	-30.87	-24.27	-19.77
Reduction 10%			
Share of Responders	0.78	0.18	0.17
Household Treatment Effect (%)	-31.95	-28.79	-24.94
Reduction 15%			
Share of Responders	0.71	0.14	0.11
Household Treatment Effect (%)	-33.73	-33.33	-30.83

Notes. The reported results present the average household-level estimated treatment effects from estimating specification (2), focusing only on households deemed to be responders. We vary the definition of responders whose coefficients are negative and achieve percentage reductions at or above thresholds ranging from 2.5%, 5%, 7.5%, 10%, to 15%. We present the marginal effects to be a percentage change in consumption using the transformation $100 \times (exp(\widehat{\beta}_i) - 1)$. Share of responders represents the percentage of households within a demand response program that are classified as responders.

Back

Opportunity Costs of Time: Exit Survey

- Implemented an exit survey in June 2023
- Goal: Correlate HH-specific estimates with measures for opportunity costs of time
- High response rates: 75% Central, 71% Tech, 69% Manual

Back

Opportunity Costs of Time: Exit Survey

- *"What is your approximate household income?"*
  - $< 50k, [50 - 99k], [100 - 149k], [150 - 200k], > 200k$
- *"For events that you noticed, how often was it worth your time to participate by attempting to reduce your consumption?"*
  - Never, Sometimes, About half the time, Most of the time, Always

Back

Opportunity Costs of Time: Exit Survey

- For each household i:

$$Y_i = \beta_0 + \beta_1 I_i + \beta_2 Z_i + \beta_3 G_i + \gamma X_i + \epsilon_i$$

- I_i = Income category
- Z_i = Worth time
- G_i = DR program indicator
- X_i is a vector of controls for HH appliances (hot water heater, # of thermostats, EV charger type) and single family home indicator

Back

Opportunity Costs of Time: Exit Survey

Table: Household Treatment Effect on Worth Time and Income

	Coefficient	Std. Error	P-Value
Worth Time			
Sometimes	-3.4934	2.2404	0.1189
Half of the Time	-6.3097	2.4711	0.0107
Most of the Time	-9.0212	2.4337	0.0002
Always	-15.0505	2.9170	0.0000
Income			
50 - 99k	5.5255	4.5976	0.2294
100 - 149k	7.3086	4.6087	0.1128
150 - 200k	9.8930	4.5909	0.0312
>200 k	9.7378	4.5432	0.0321
Program Indicators			
Central	-17.2308	1.7559	0.0000
Tech	-1.3486	1.6000	0.3993

Back

Exit Survey: Responders vs Non-Responders

Table C5. Balance by Exit Survey Response (Pre-Treatment Data)

	Yes	No	p-value
Cumul. kWh			
Winter	5,229	5,892	0.04
	(2,810)	(3,199)	
Spring	3,675	4,167	0.02
	(1,788)	(2,104)	
Summer	2,614	3,155	0.01
	(1,492)	(2,142)	
Fall	3,528	4,012	0.02
	(1,721)	(2,016)	
Load Factor			
Winter	24.96	25.21	0.78
	(8.61)	(8.89)	
Spring	19.82	19.98	0.83
	(6.64)	(6.93)	
Summer	16.56	17.21	0.37
	(6.87)	(6.76)	
Fall	18.66	19.12	0.51
	(5.91)	(6.72)	
Electric Vehicle	0.24	0.32	0.05
	(0.42)	(0.47)	
BaseBoard Heating	0.66	0.64	0.71
	(0.47)	(0.48)	
Air Conditioning	0.47	0.51	0.32
	(0.50)	(0.50)	
Electric Hot Water	0.72	0.70	0.56
	(0.45)	(0.46)	
House Duplex	0.83	0.82	0.71
	(0.37)	(0.38)	
Median Income	86,377	87,434	0.55
	(19,853)	(19,835)	
Observations	429	174	

Back

Device-Level Estimates

Questions:

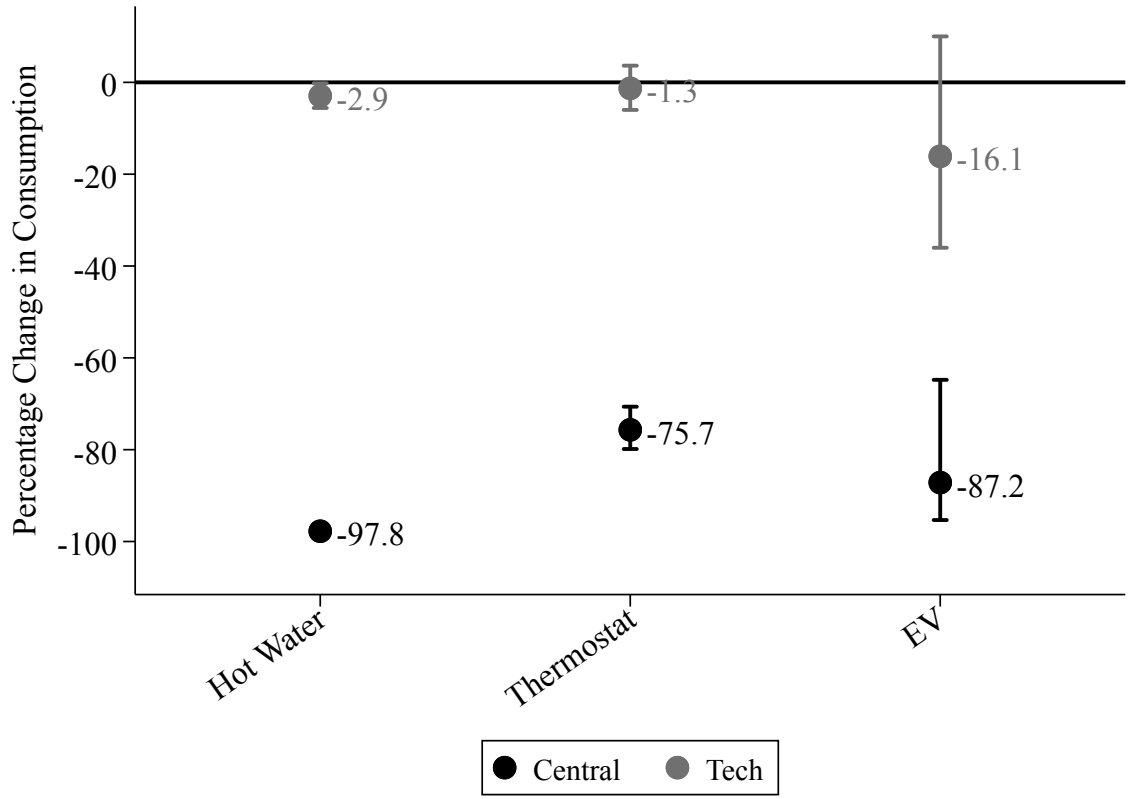
1. What specific device-level adjustments are driving the demand reductions, particularly for Central?
2. What do these adjustments say about the private cost of automation?

Use hourly device-specific data to estimated device-level estimated treatment effects for Central and Tech programs

Back

Device-Level Estimates

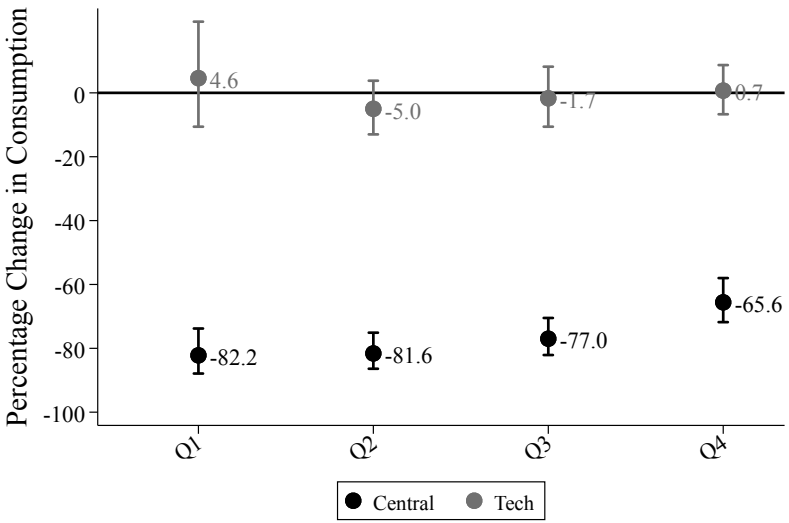
Figure: Device-Specific Estimated Treatment Effects - Central and Tech Programs



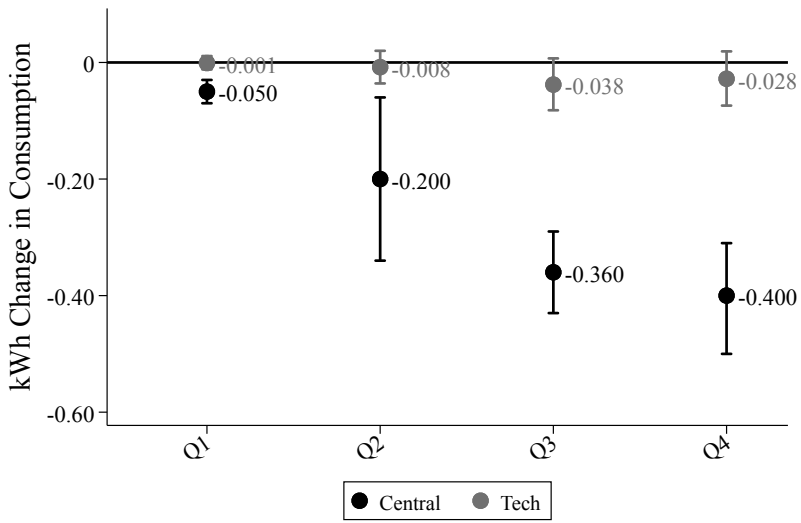
Back

Device-Level Estimates

Figure: Thermostat Estimated Treatment Effects by HDD Quartile - Central and Tech Programs



(a) Log Specification

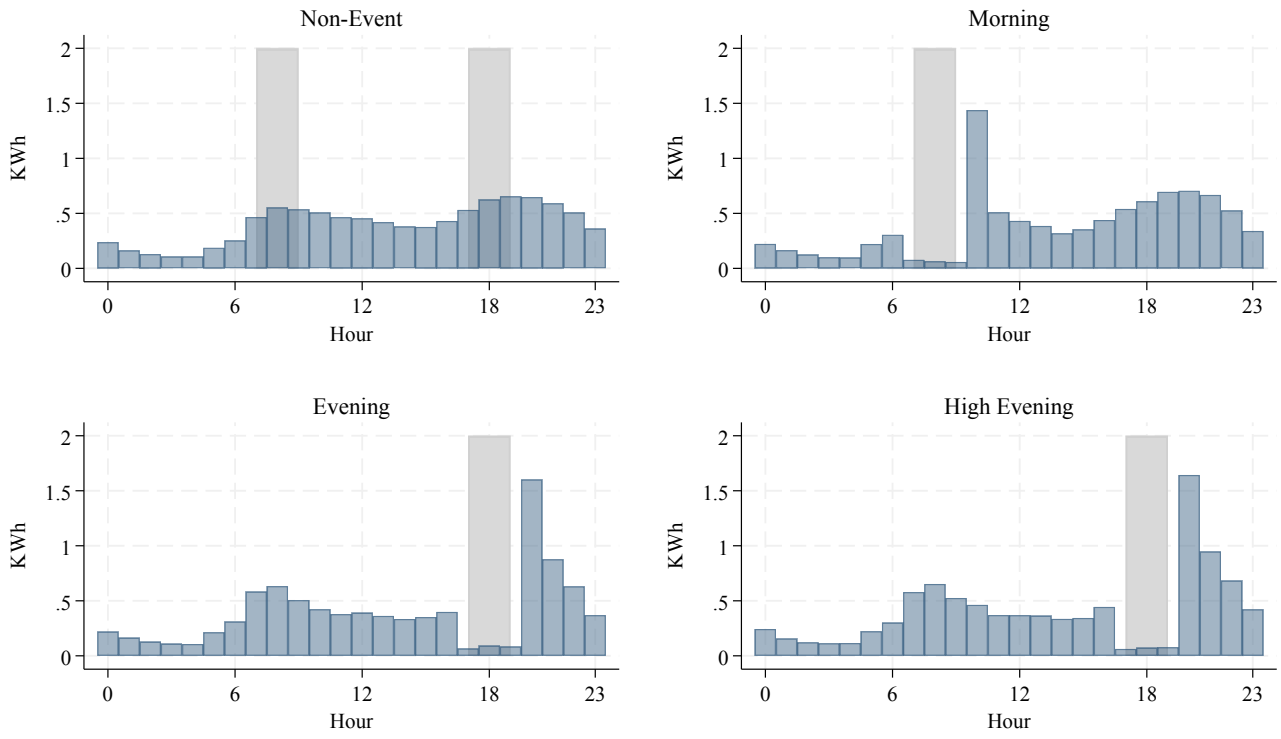


(b) Linear Specification

Back

Device-Level Descriptive Results: Hot Water Heaters

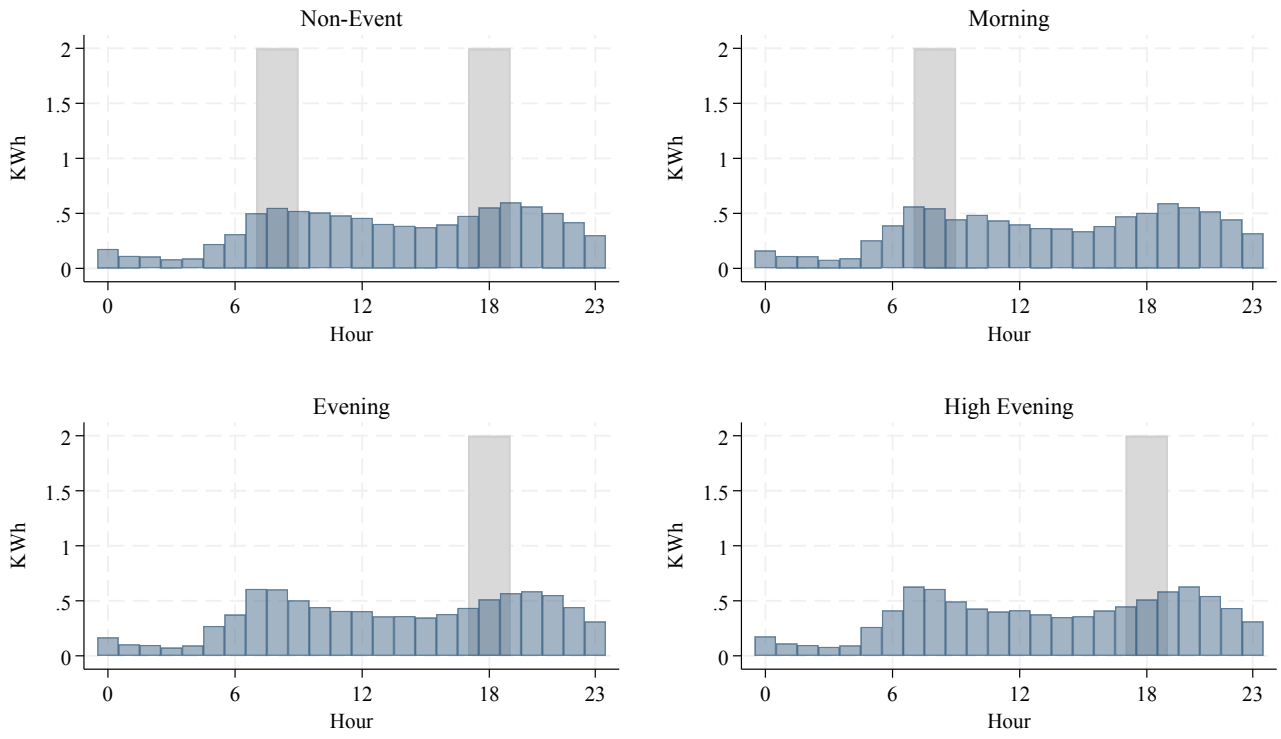
Average Hot Water Usage by Day-Type and Program - Central



Back

Device-Level Descriptive Results: Hot Water Heaters

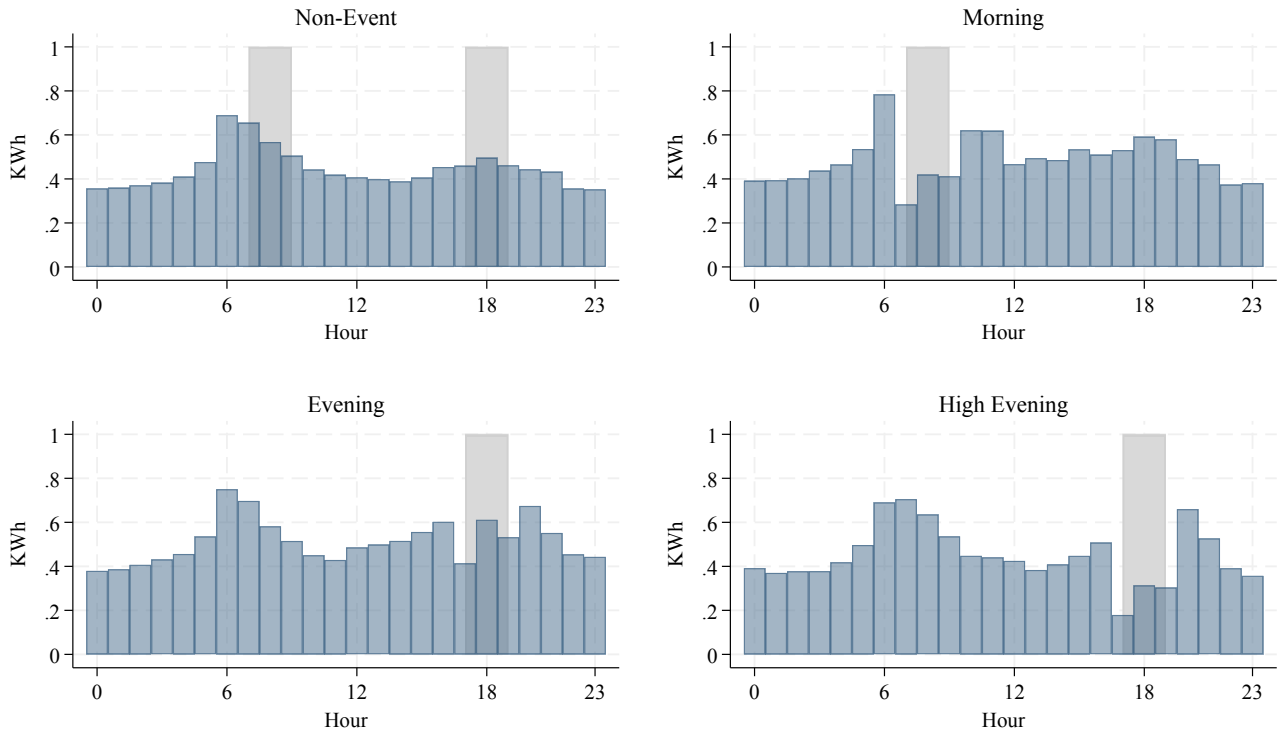
Average Hot Water Usage by Day-Type and Program - Tech



Back

Device-Level Descriptive Results: Baseboard Thermostat

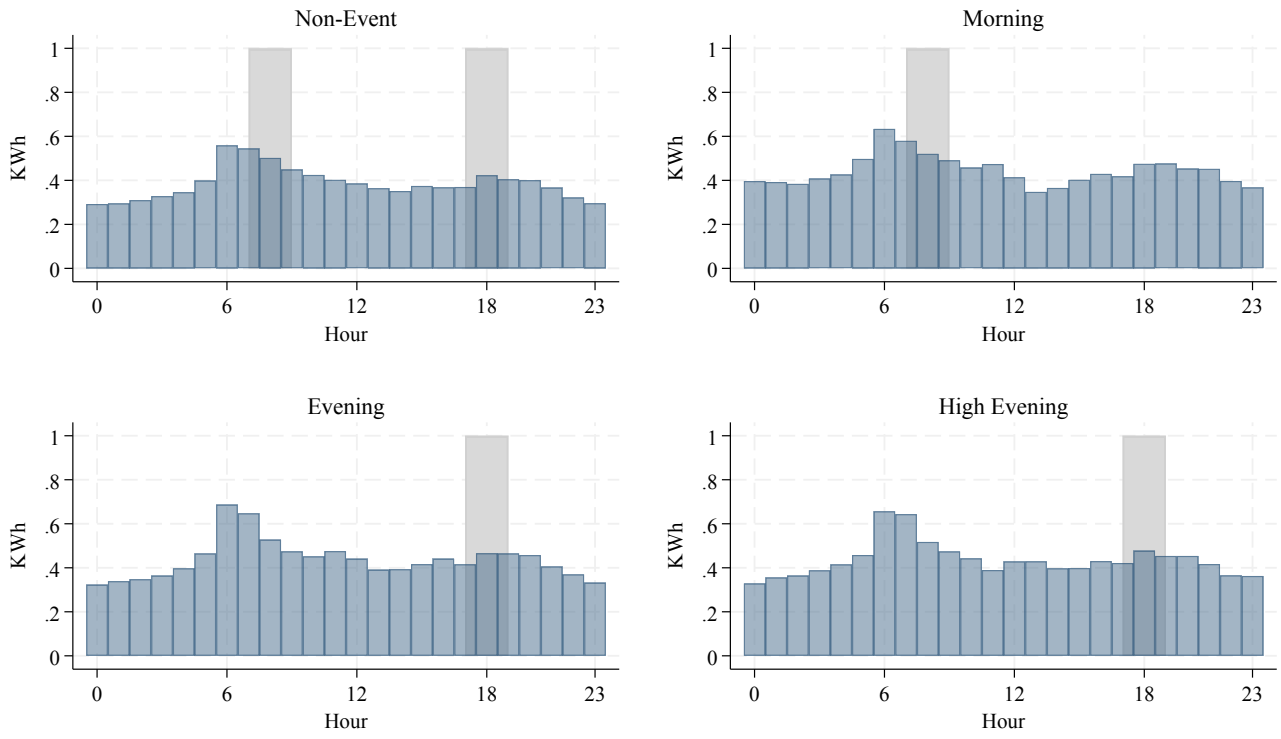
Average Baseboard Thermostat Usage by Day-Type and Program - Central



Back

Device-Level Descriptive Results: Baseboard Thermostat

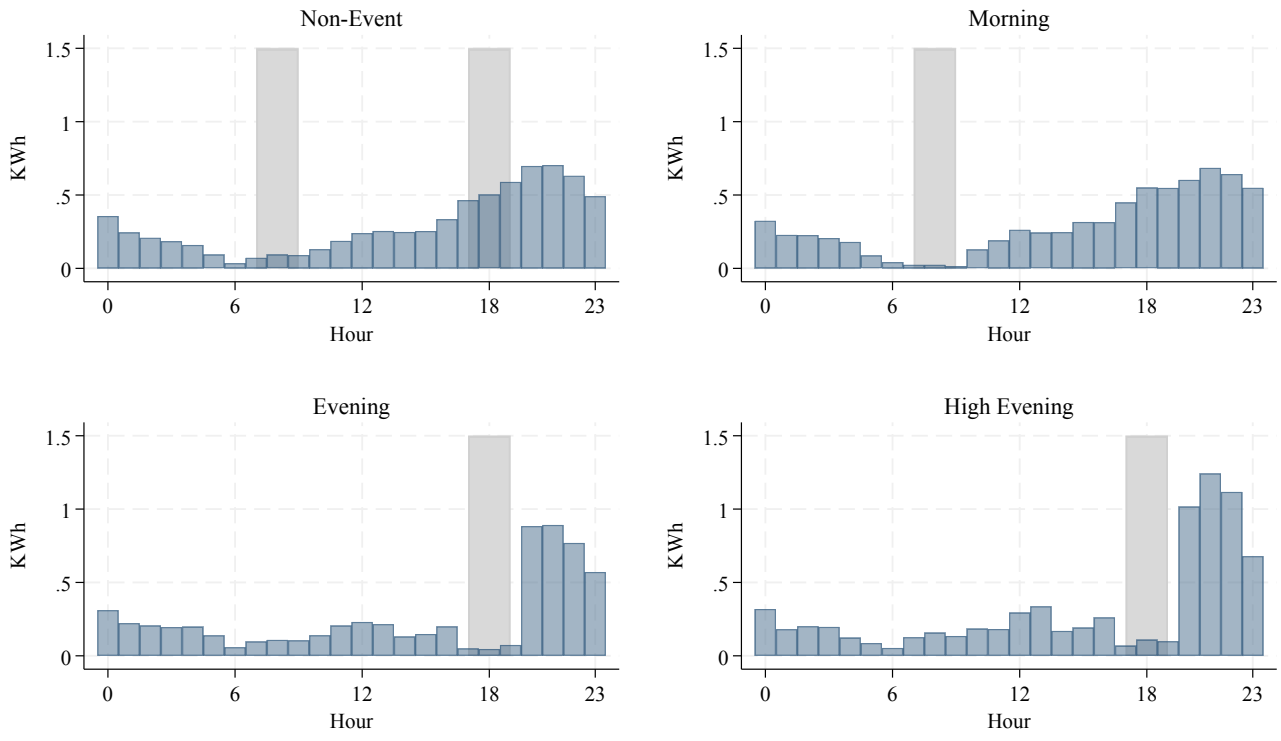
Average Baseboard Thermostat Usage by Day-Type and Program - Tech



Back

Device-Level Descriptive Results: EV

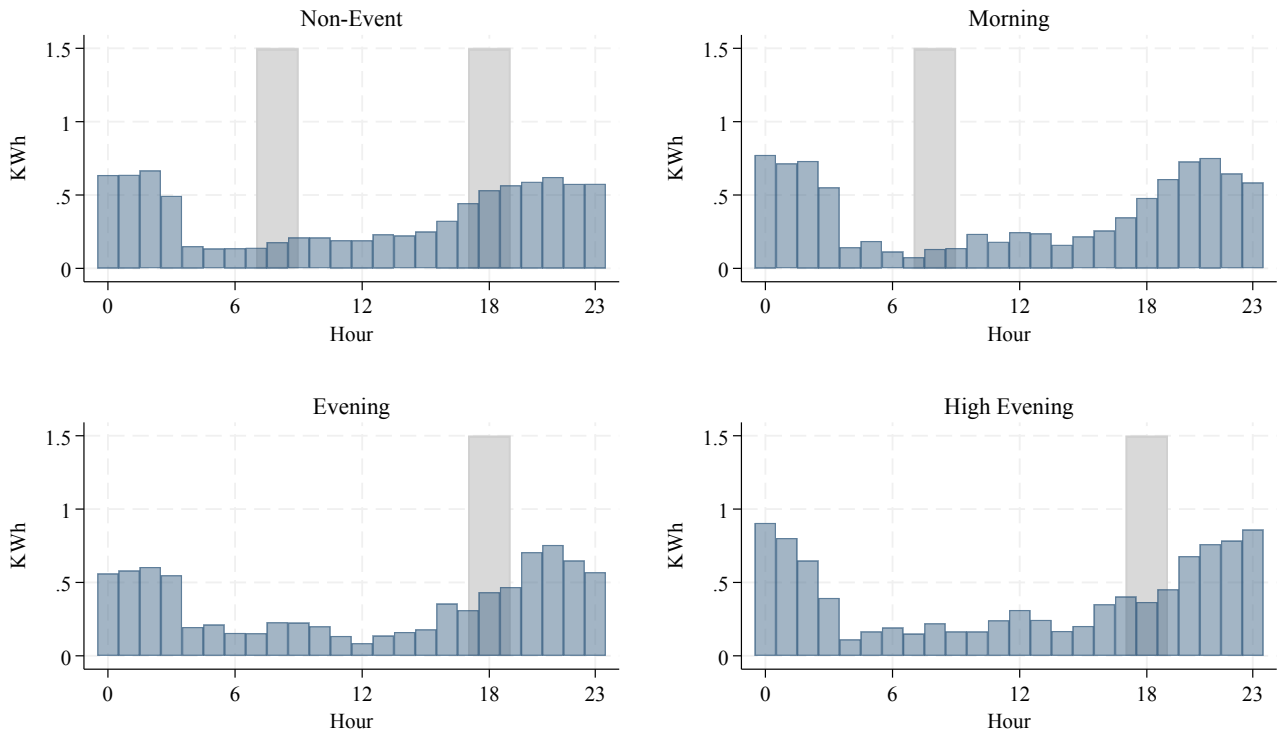
Average EV Usage by Day-Type and Program - Central



Back

Device-Level Descriptive Results: EV

Average EV Usage by Day-Type and Program - Tech



Back

External Validity - Census Data

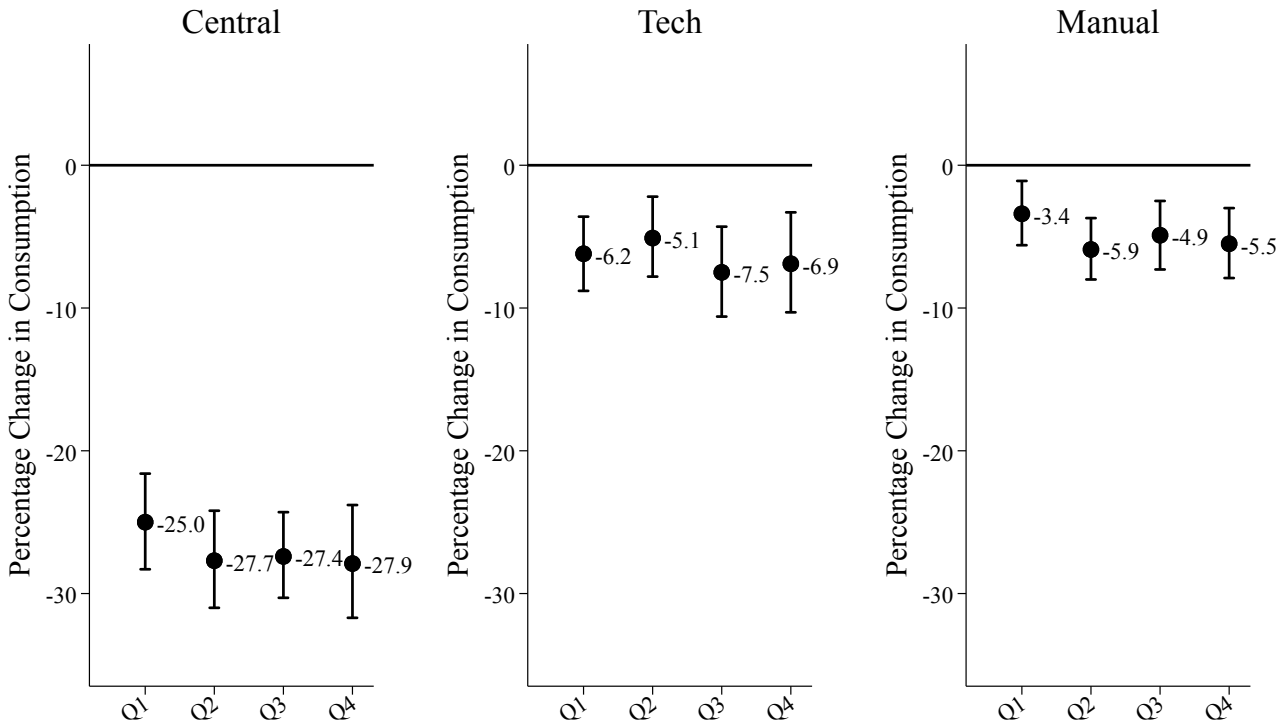
Table A3. Comparison of Census Dissemination Area Characteristics

	Metro Area	Invited	Accepted
Mean Age	41.8	41.8	41.9
	(6.1)	(6.3)	(6.3)
Median Household Income	78,518.2	86,828.9	87,055.4
	(24,875.0)	(20,657.2)	(20,420.7)
Single Detached (%)	39.7	52.8	54.2
	(31.8)	(27.8)	(26.8)
Owner Occupied (%)	68.1	76.8	77.3
	(21.8)	(15.2)	(14.5)
High School Education (%)	29.1	29.1	29.0
	(6.7)	(6.2)	(6.2)
Post Secondary Education (%)	56.3	58.0	58.1
	(11.7)	(9.3)	(9.0)
Canadian Citizenship (%)	88.7	92.4	92.8
	(8.4)	(5.9)	(5.6)
Immigrant (%)	34.8	25.7	24.2
	(17.3)	(14.6)	(13.6)
Visible Minority (%)	39.3	25.7	23.5
	(27.9)	(23.8)	(22.0)
Observations	3,382,162	1,661	968

Back

External Validity - System Load

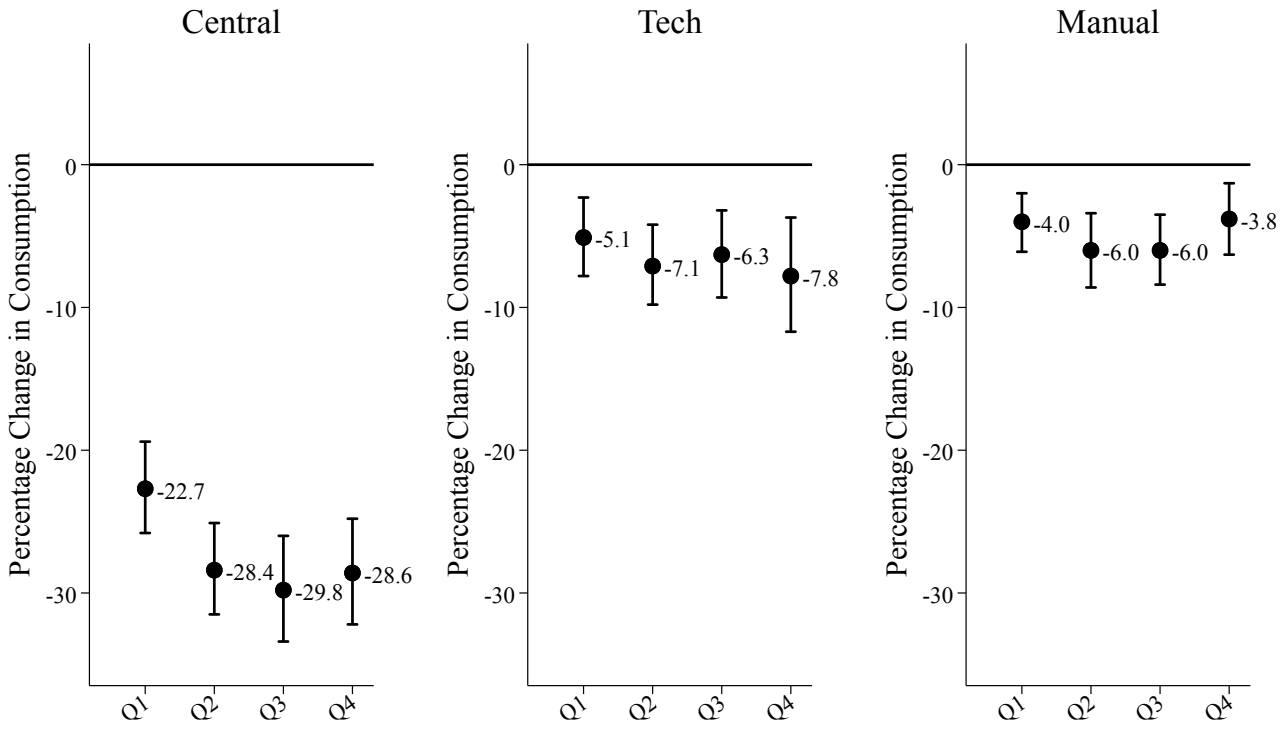
Average Treatment Effect of Participants by Program and Daily System Peak Demand Quartile



Back

External Validity - HDD

Average Treatment Effect of Participants by Program and HDD Quartile



Back