Distortionary Fundraising for Energy Efficiency Subsidies: Implications for Efficient and Equitable Policy Design

Chris Bruegge
Stanford University

February 2, 2018
Figure shows total US expenditures on energy efficiency subsidies. Source: ACEEE 2016 Scorecard
Research Objectives

Program Evaluation
1. What is the effect of these policies on total welfare?
2. Who benefits from the policies?

Program Design
3. How can policy makers improve equity and efficiency?
Research Objectives

Program Evaluation

1. What is the effect of these policies on total welfare?
   ▶ Policy costs are 4x greater than benefits

2. Who benefits from the policies?
   ▶ Households in poorer zipcodes experience 50% greater loss of consumer surplus (in $)

Program Design

3. How can policy makers improve equity and efficiency?
   ▶ Lump sum fundraising, lower participation hassle costs, and means-tested eligibility criteria
Typical Program Evaluations

Subsidy Channel Impacts

- **Energy Use**: Boomhower and Davis (2017), Davis (2008), Davis et al. (2014), Fowlie et al. (2015), Houde and Aldy (2016), Gillingham et al. (2006, 2009)
- **Inframarginal Participation**: Boomhower and Davis (2014), Houde and Aldy (2014)

This paper

- I show *distortionary energy price changes* causes >80% of total energy savings and >35% of welfare loss
Methodology

Discrete - Continuous Model

- Two relevant prices, two choices
  1. Energy price -> energy consumption, appliance purchase
  2. Subsidy -> appliance purchase, energy consumption

Primary Data

- Monthly household-level billing data from large utility
- Household-level washing machine rebate claims
Roadmap

- Utility Maximization Problem
  - Discrete-Continuous Choice Model
  - Optimal Energy Consumption and Appliance Choices

- Data / Identification

- Program Evaluation Results

- Program Design Counterfactual
Appliance Purchase Choices

J=A

J=B

J=C

No Purchase
Energy Star Purchasers Can Claim Rebate

J=A

J=A+

$50 REBATE

J=B

J=C

No Purchase
Households \((i)\) purchase appliances \((j)\) to consume services

\[
S_{ij} = \gamma_j \cdot kWh_i
\]

- Energy Star appliances cost more to purchase
  - \(p^a_{ij}\): Appliance purchase price
- Energy Star appliances produce services at lower cost
  - \(p^s_{ij} = p^{kWh}_i / \gamma_j\): Price of energy services
Expected Utility Maximization

\[
\max_{(j, s)} \left\{ n_{i0} + \xi_{ij} + \sigma_g \epsilon_{ij} + E^\nu \left[ \sum_t \delta^t \left( n_{it} + \frac{1}{2 \beta_{g_i}} (s_{ij} - \alpha_i - \nu_{ij})^2 \right) \right] \right\}
\]

Period 0 Purchase Utility

\[
E^\nu \left[ \sum_t \delta^t \left( n_{it} + \frac{1}{2 \beta_{g_i}} (s_{ij} - \alpha_i - \nu_{ij})^2 \right) \right]
\]

Expected PDV Future Operating Utility

s.t. \[ I_{i0} \geq n_{i0} + p_{ij} \],
\[ I_{it} \geq n_{it} + p_{s_{ij}} \cdot s_{ij}, \quad t \in \{1, \ldots, 120\}. \]

Choice Variables

\[ j: \text{ Appliance choice} \]
\[ s: \text{ Energy service consumption} \]
\[ n: \text{ Numeraire} \]
Description of Discrete Choice Fixed Effects

<table>
<thead>
<tr>
<th>Discrete Choice</th>
<th>$\xi_{ij}$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>Normalization</td>
</tr>
<tr>
<td>B</td>
<td>$\tau g_i$</td>
<td>Shopping Disutility</td>
</tr>
<tr>
<td>A</td>
<td>$\tau g_i + \kappa g_i$</td>
<td>$\xi_B$ + Energy Star Feature Utility</td>
</tr>
<tr>
<td>$A^+$</td>
<td>$\tau g_i + \kappa g_i + \theta_i$</td>
<td>$\xi_A$ + Rebate Form Disutility</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discrete Choice</th>
<th>$\epsilon_{ij}$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>$\epsilon_i C$</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>$\epsilon_i B$</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$\epsilon_i A$</td>
<td></td>
</tr>
<tr>
<td>$A^+$</td>
<td>$\epsilon_i A$</td>
<td>Same appliance as A</td>
</tr>
</tbody>
</table>

Notes: The variable $g_i$ takes value between 1 and 5 corresponding to each of the five quintiles of the zipcode income distribution. If household $i$ lives in a zipcode whose median household income is in the bottom 20% of the distribution of zipcode-level median household incomes, then $g_i = 1$. This allows for the parameters to be heterogeneous for household in neighborhoods of different income levels.
Expected Utility Maximization

\[
\max_{(j, \bar{s})} \quad \left( n_{i0} + \xi_{ij} + \sigma_{g\bar{s}} \epsilon_{ij} \right) + E_{\nu} \left[ \sum_{t} \delta^{t} \left( n_{it} + \frac{1}{2\beta_{g\bar{s}}} (s_{ijt} - \alpha_{i} - \nu_{ijt})^{2} \right) \right]
\]

Period 0 Purchase Utility

Expected PDV Future Operating Utility

s.t.
\[
\begin{align*}
I_{i0} & \geq n_{i0} + p_{ij}^{a}, \\
I_{it} & \geq n_{it} + p_{ijt}^{s} \cdot s_{ijt}, \quad t \in \{1, \ldots, 120\}.
\end{align*}
\]

Choice Variables

- **j**: Appliance choice
- **s**: Energy service consumption
- **n**: Numeraire
Error Accounting and Stationarity

\[ E_{\nu}[U(j, \tilde{s})] = n_{i0} + \xi_{ij} + \sigma_{gi}\epsilon_{ij} + E_{\nu}\left[ \sum_t \delta^t \left( n_{it} + \frac{1}{2\beta_{gi}}(s_{ijt} - \alpha_i - \nu_{ijt})^2 \right) \right] \]

Structural Error Terms

- Household knows realization of \( \epsilon_{ij}, \theta_i, \) and \( \alpha_i \)
- Households + econometrician know distribution of \( F_{g_{ij},\nu(\nu)} \);
  Household observes realization of \( \nu \) after durable purchase

Stationary environment with respect to

- Technology, energy / appliance prices, distribution \( F_{g_{ij},\nu(\nu)} \)
Roadmap

- Utility Maximization Problem
  - Discrete Choice / Continuous Choice
  - Optimal Energy Consumption and Appliance Choices

- Data / Identification

- Program Evaluation Results

- Program Design Counterfactual
Optimal Energy Service Consumption

\[ s^*_{ijt} = \alpha_i + \beta_{g_i}^s p^s_{ijt} + \nu_{ijt} \]

Optimal Appliance Choice

\[ V_{ij} = \mathbb{E}_\nu[U(s^*_{ijt} | j)] \]
\[ Pr_{ij} = Pr(V_{ij} > \max(V_{ik}), j \neq k) \]
Roadmap

- Utility Maximization Problem
- Data / Identification
  - Primary Dataset and Latent Choices
  - Identification
- Program Evaluation Results
- Program Design Counterfactual
## Primary Utility Billing Dataset

<table>
<thead>
<tr>
<th>Dependent Variables</th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013 Program Participation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_j(A^+)$ Washer</td>
<td>84,020</td>
<td>0.018</td>
<td>0.13</td>
</tr>
<tr>
<td><strong>Monthly HH Energy Use (kWh)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full Sample: Oct ‘10 - Aug ‘15</td>
<td>2,520,360</td>
<td>745.86</td>
<td>453.53</td>
</tr>
<tr>
<td>Estimation Sample: Jan ‘13, Jan ‘14</td>
<td>168,040</td>
<td>744.93</td>
<td>438.65</td>
</tr>
</tbody>
</table>

Notes: Data were obtained under a non-disclosure agreement that prohibits me from sharing the name of the utility. I don’t use the full billing sample in estimation for computational reasons, although this doesn’t affect the consistency of my parameter estimates. I also observe parcel attributes and the household’s zipcode.
Observe $\Pr_{A^+}$ and $\Pr_{(A^+)^c}$

Period

Purchase

ES

Rebate $(A^+)$

No Rebate $\in (A^+)^c$

Non-ES $\in (A^+)^c$

No Purchase $\in (A^+)^c$

Need two more probabilities to identify the model
2009 RECS survey has parcel and appliance purchase info.

- Representative sample from same state as primary data

<table>
<thead>
<tr>
<th></th>
<th>RECS Mean</th>
<th>Primary Data Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income</td>
<td>67,094.63</td>
<td>66,900.64</td>
</tr>
<tr>
<td>Home Size</td>
<td>1,522.81</td>
<td>1,649.78</td>
</tr>
<tr>
<td>Home Age</td>
<td>39.80</td>
<td>32.44</td>
</tr>
<tr>
<td>Tenure at Address</td>
<td>13.69</td>
<td>14.99</td>
</tr>
<tr>
<td>N</td>
<td>1,088</td>
<td>84,020</td>
</tr>
</tbody>
</table>

Notes: Income is measured in dollars, home size is measured in square feet, and home age and tenure at the current address are measured in years.

\(^1\)Median income in household \(i\)'s zipcode
Expected Latent Purchases

Use RECS to compute $\mathbb{E}(I_{ij})$ for household with observables $x_i$

- Divide RECS households into bins
- $\hat{I}_{ij}$ is average of RECS choices in same bin
  - Assume $\mathbb{E}(I_{ij}) = \mathbb{E}(\hat{I}_{ij})$

Moment Conditions

- $\mathbb{E}(I_{iA^+} - Pr_{iA^+}) = 0$
- $\mathbb{E}(\hat{I}_{ij} - Pr_{ij}) = 0, \quad j \in \{B, C\}$
Latent Energy Service Consumption

Notation:

- Loads of Laundry per kWh: $\gamma_j$
- Washing machine share of total kWh: $\omega_{ijt}$
- Normalization: 1 kWh = 1 unit of energy services if $j = B$

Total energy service consumption is

$$S_{ijt} = \gamma_j \cdot \omega_{ijt} \cdot kWh_{it} + (1 - \omega_{ijt}) kWh_{it}$$

- Loads of Laundry
- Laundry Equivalent Services from Other Appliances
Roadmap

- Utility Maximization Problem
- Data / Identification
  - Primary Dataset and Latent Choices
  - Identification
- Program Evaluation Results
- Program Design Counterfactual
Identifying $\beta_{gi}$ and $\alpha_i$

Optimal Energy Service Consumption

$$s_{ijt} = \alpha_i + \beta_{gi}^{s}p_{ijt}^{s} + \nu_{ijt}$$

Fixed Effect Estimator to Identify $\beta$ and $\alpha$

- Within-household consumption and price variation
- Exogenous changes to price schedule
An observation is a household month, \((y_{it}, x_{it})\). The y-axis shows within household energy price variation and the x-axis shows within household energy consumption variation. This “within” variation is used to identify the parameters \(\beta_{gi}\). The plot shows that energy consumption is relatively inelastic.
An observation is a market. Marker size is proportional to the number of households in the market. Participation rate shows the mean of $I_i(A^+)$ in each market.
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
  - Parameter Estimates
  - Economic Efficiency
  - Distributional Equity
- Program Design Counterfactual
Each marker represents the average price elasticity of demand for energy service consumption in zipcode income quintile $g_i$. Robust standard errors are computed using the delta method. Price elasticity $= \frac{\beta_{g_i}}{\sigma^s/s}$. 

Price Elasticity of Energy Service Demand
The plot shows the simulated empirical distribution of $\theta_{g_i} = \lambda_{g_i} \cdot Rayleigh(1)$. The same 100 draws from a Rayleigh(1) distribution were used for each income quintile. Notice that the distribution increases in income in a first-order-stochastic-dominance sense.
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
  - Parameter Estimates
  - Economic Efficiency
  - Distributional Equity
- Program Design Counterfactual
“Total Surplus” includes

- Size of the environmental externality
- Consumer and producer surplus
Energy Consumption and Environmental Benefits

\[ E[kwh|(p^a, p^s)] = \sum_{i=1}^{N} \sum_{j} (Pr_{ij}(p^a, p^s) \cdot kWh_{ij}(p^a, p^s)) \]

- \((p^a_{ij}, p^s_{ij})\): No subsidy counterfactual
- \((p^a_{ij, act}, p^s_{ij, act})\): Actual program prices
- \((p^a_{ij, act}, p^s_{ij, 0})\): Fixed price fundraising
## Environmental Benefits

<table>
<thead>
<tr>
<th></th>
<th>Variable (per-kWh) Charge</th>
<th>Fixed Monthly Charge</th>
<th>Ratio (2) / (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Savings (kWh)</td>
<td>60,114</td>
<td>10,610</td>
<td>0.177</td>
</tr>
<tr>
<td>Social Cost of 1 kWh ($)</td>
<td>.1</td>
<td>.1</td>
<td></td>
</tr>
<tr>
<td>Environmental Benefit ($)</td>
<td>6,011.40</td>
<td>1,061.00</td>
<td>0.177</td>
</tr>
</tbody>
</table>

Notes: Energy savings in the first column are model-based estimates of reductions in my sample due to the actual program. This column incorporates both the subsidy and the energy price effects. In the second column, energy savings are entirely due to the subsidy channel since the fixed-fee fundraising is non-distortionary. Note that an evaluation that mistakenly assumes non-distortionary fundraising when in fact subsidy monies are raised through marginal electricity prices only captures 17.7% of the effect on energy consumption.
## Program Participation

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(\text{Marginal Participants})$</td>
<td>419.8</td>
</tr>
<tr>
<td>$E(\text{Inframarginal Participants})$</td>
<td>1,066.0</td>
</tr>
<tr>
<td>$E(\text{Total Participants})$</td>
<td>1,485.8</td>
</tr>
</tbody>
</table>

Notes: Inframarginal participation was computed based on simulation so I could account for purchasers who bought an energy efficient appliance because of both the subsidy and the electricity price change channels. In expectation, less than one household changed their because of the energy price change, but almost one third purchased an Energy Star durable because of the subsidy incentive.
Kaldor-Hicks Economic Efficiency

“Total Surplus” includes

- Size of the environmental externality
- Consumer and Producer surplus
Net Benefits with an Environmental Market Failure

\[ \Delta CS = E[\max(V_{ij}(p_{ij}^a,*, p_{ij}^s,*))] - E[\max(V_{ij}(p_{ij}^a,0, p_{ij}^s,0))] \]

<table>
<thead>
<tr>
<th>Variable (per-kWh) Charge</th>
<th>Fixed Monthly Charge</th>
<th>Ratio (2) / (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Consumer Surplus</td>
<td>-$75,646</td>
<td>-$63,987</td>
</tr>
<tr>
<td>Change in Producer Surplus</td>
<td>$50,207</td>
<td>$50,268</td>
</tr>
<tr>
<td>Environmental Benefit</td>
<td>$6,011.40</td>
<td>$1,061.00</td>
</tr>
<tr>
<td><strong>Net Welfare Change</strong></td>
<td><strong>-$19,428</strong></td>
<td><strong>-$12,658</strong></td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that the disutility \( \theta \) of filling out a rebate application is a real economic cost. This assumption will be relaxed in the next slides.
\[ V_j = I_0 - p_j^a + \xi_j(\theta) + \sigma \epsilon_j + \Gamma \cdot \mathbb{E}_\nu \left[ \sum_t \delta^t (l_t - p_j^s \left( \frac{1}{2} \beta^s p_j^s + \alpha + \nu_{jt} \right)) \right] \]

Allcott et al (2014)

- Decision Utility: \( \Gamma < 1 \)
- Experience Utility: \( \Gamma = 1 \)
## Environmental and Appliance Market Failures

### Panel A: No Appliance Market Failure

<table>
<thead>
<tr>
<th></th>
<th>Variable (per-kWh) Charge</th>
<th>Fixed Monthly Charge</th>
<th>Ratio (2) / (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Welfare Change</strong></td>
<td>-$19,428</td>
<td>-$12,658</td>
<td>0.651</td>
</tr>
</tbody>
</table>

### Panel B: 25% Undervaluation of Consumption Utility

<table>
<thead>
<tr>
<th></th>
<th>Variable (per-kWh) Charge</th>
<th>Fixed Monthly Charge</th>
<th>Ratio (2) / (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Change in Consumer Surplus</strong></td>
<td>-$103,860</td>
<td>-$63,570</td>
<td>0.612</td>
</tr>
<tr>
<td><strong>Change in Producer Surplus</strong></td>
<td>$50,207</td>
<td>$50,268</td>
<td>0.999</td>
</tr>
<tr>
<td><strong>Environmental Benefit</strong></td>
<td>$6,011.40</td>
<td>$1,061.00</td>
<td>0.177</td>
</tr>
<tr>
<td><strong>Net Welfare Change</strong></td>
<td>-$47,646</td>
<td>-$12,241</td>
<td>0.257</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that the disutility $\theta$ of filling out a rebate application is a real economic cost. This assumption will be relaxed in the next slides.
Hassle Costs in the Utility Function

\[ V_{A^+} = l_0 - p_{A^+}^a + \tau + \kappa + \theta^* + \sigma \varepsilon_j + \]
\[ \mathbb{E}_\nu \left[ \sum_t \delta^t (l_t - p_j^S (\frac{1}{2} \beta^S p_{A^+}^s + \alpha + \nu_j)) \right] \]

Can relax assumption that \( \theta \) is a welfare cost

- **Decision Utility**: \( \theta^* = \theta \)
- **Experience Utility**: \( \theta^* \leq \theta \)
Environmental and Appliance Market Failures, $\theta^* = 0$

<table>
<thead>
<tr>
<th>Panel</th>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel A: 25% Undervaluation of Consumption Utility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net Welfare Change</td>
<td>-$47,646</td>
<td>-$12,241</td>
<td>0.257</td>
</tr>
<tr>
<td>Panel B: 25% Undervaluation, $\theta^* = 0$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Change in Consumer Surplus</td>
<td>-$54,434</td>
<td>-$14,144</td>
<td>0.260</td>
</tr>
<tr>
<td>Change in Producer Surplus</td>
<td>$50,268</td>
<td>$50,207</td>
<td>0.999</td>
</tr>
<tr>
<td>Environmental Benefit</td>
<td>$6,011.40</td>
<td>$1,061.00</td>
<td>0.177</td>
</tr>
<tr>
<td>Net Welfare Change</td>
<td>$1,846</td>
<td>$37,124</td>
<td>20.112</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume the parameter $\theta^* = \theta$ enters the decision utility, but is a “mistake” rather than a real economic cost; in the experience utility, $\theta^* = 0$. 
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
  - Parameter Estimates
  - Economic Efficiency
  - Distributional Equity
- Program Design Counterfactual
Notes: The figure shows the expected change in consumer surplus (measured in dollars) for the distortionary program and the non-distortionary program. Notice that moving fundraising to a fixed-fee rather than an increase to the marginal price reduces loss of consumer surplus in all but the wealthiest 20% of zipcodes.
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
- Program Design Counterfactual
### Means-tested Policy at the Point of Sale

<table>
<thead>
<tr>
<th>Zipcode</th>
<th>Income Quintile</th>
<th>Fixed Fee (per HH)</th>
<th>Subsidy (per HH)</th>
<th>ΔCS (per HH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>$1.72</td>
<td>$50.00</td>
<td>$3.60</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>$1.72</td>
<td>$0.00</td>
<td>-$1.72</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>$1.72</td>
<td>$0.00</td>
<td>-$1.72</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>$1.72</td>
<td>$0.00</td>
<td>-$1.72</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>$1.72</td>
<td>$0.00</td>
<td>-$1.72</td>
</tr>
</tbody>
</table>

× Number of Households per Quintile $16,804

- Change in Consumer Surplus $-54,996
- Change in Producer Surplus $1,368,200
- Environmental Benefit $1,155

Net Welfare Change $1,314,359

Notes: This table shows the net welfare change that would be associated with a single program year of a means-tested point of sale policy ($\theta = 0$) if the regulator valued $1 of income the same for all households. Notice that if producer surplus was given a weight of 0, then this policy would not improve social welfare. Several alternatives to this possible policy change are considered in the appendix.
Conclusion

Today

- Importance of energy price changes for program evaluation
- Current program regressive, reduces consumer surplus
- Efficiency / equity improving policies
  - Fundraising through fixed monthly charges
  - Point of sale rebate, means tested eligibility
Thank You!

cbruegge@stanford.edu
Energy Efficiency Subsidies

Perceived market failures

- Energy consumption externality
- Appliance market failure (e.g. landlord-tenant incentives)
“revenues used to fund these programs [shall be] ... collected on the basis of usage” — CA PUC Code
Energy Savings From Electricity Price Increases

\[ \text{\% Savings Per Customer / Month} = \text{Price Elasticity} \cdot \text{Price Change} \]

\[
\begin{align*}
0.52\% &= \text{Price Elasticity} \cdot 3.3\% \\
-0.16 &= \text{Price Elasticity} \cdot 3.3\%
\end{align*}
\]

Estimates of the Price Elasticity

- Ito (2014): -0.08
- Reiss et al (2005): -0.39
- This paper: -0.16
Energy Savings through Appliance Replacement

\[
\text{% Savings Per Customer / Month} = \ \frac{\text{Savings per Participant}}{5\%} \times \frac{\text{Marginal Participants}}{10\%} \times \frac{\text{Share of Participants}}{2.5\%}
\]

0.013% = Savings per Participant

Estimates of the Share of Marginal Participants

- Boomhower and Davis (2014): 50%
- Houde and Aldy (2014): 8%
- This paper: 3%
<table>
<thead>
<tr>
<th>Appliance Channel</th>
<th>Energy Price Channel</th>
<th>Energy Price % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative</td>
<td>0.125</td>
<td>0.5</td>
</tr>
<tr>
<td>Midrange</td>
<td>0.013</td>
<td>1.0</td>
</tr>
<tr>
<td>High</td>
<td>0.001</td>
<td>2.5</td>
</tr>
<tr>
<td>My Estimate</td>
<td>~</td>
<td>~</td>
</tr>
</tbody>
</table>

Notes: Baseline consumption is roughly 700kWh / month per household. The conservative estimate uses an own price elasticity of -.08, a savings rate of 10% per participant from Fowlie et al (2017), and 50% marginal participants. The savings rate of 10% for the weatherization is likely to be substantially higher than the savings rate for the average program, which is the correct number to include here. Midrange estimates are -.16, 5%, and 10%, and high estimates are -.39, 1%, and 3% for the price elasticity, savings per household, and fraction of marginal participants respectively. My estimates for the first two columns aren’t comparable since I evaluate two specific programs rather
Direct Utility $\alpha$ Parameter

Expected Bliss Consumption of Energy Services ($\alpha_i$)

$\bar{U}$ Indifference Curve

$E[PDV(\text{Numeraire})]$ vs. $E[PDV(\text{Energy Services})]$
Conditional Indirect Utility

Estimable Equations

- No washing machine purchase (j=D)

\[ V_{iD} = I_i + V^*(p_{sD}, X_i) + \epsilon_{iD} \]

\( p^s \) = Price of Energy Services; \( X = \{\text{Home Size, Home Age}\} \)

- Non-Energy Star purchase (j=C)

- Energy-Star + No Rebate (j=B)

- Energy-Star + Rebate (j=A)
Conditional Indirect Utility

- No washing machine purchase (j=D)
- Non-Energy Star purchase (j=C)

\[ V_{iC} = I_i - p_{iC}^a + \tau + V^*(p_{iC}^s, X_i) + \epsilon_{iC} \]

- Energy-Star + No Rebate (j=B)
- Energy-Star + Rebate (j=A)
Conditional Indirect Utility

- No washing machine purchase (j=D)
- Non-Energy Star purchase (j=C)
- Energy-Star + No Rebate (j=B)

\[ V_{iB} = I_i - p_{iB}^a + \tau + \kappa + V^*(p_{iB}^s, X_i) + \epsilon_{iB} \]

- Energy-Star + Rebate (j=A)
Conditional Indirect Utility

- No washing machine purchase (j=D)
- Non-Energy Star purchase (j=C)
- Energy-Star + No Rebate (j=B)
- Energy-Star + Rebate (j=A)

\[ V_{iA} = I_i - p^a_{iA} + \tau + \kappa + \theta_i + V^*(p^s_{iA}, X_i) + \epsilon_{iB} \]

\[ = V_{iB} + \text{Subsidy} + \theta_i \]
Distributional Assumptions

\[ F_{\bar{\epsilon}_i}(\epsilon_iA, \epsilon_iB, \epsilon_iC) = \exp\left(-\left(\exp(-\epsilon_iA/\rho) + \exp(-\epsilon_iB/\rho)\right)^\rho - \exp(-\epsilon_iC)\right) \]

\[ \theta \sim \lambda_{g_i} \cdot Rayleigh(1) \]

Integrate over \( \theta, \epsilon \) to get market shares:

\[ Pr_{iA^+} = \int_{-\text{Subsidy}}^0 f_{g_i, \theta}(\theta) \cdot \frac{(1+\exp(-((\mu_{iA^+}(\theta) - \mu_{iB})/\sigma_{g_i}\rho))^{\rho-1}}{\exp(-\mu_{iA^+}(\theta)/\sigma_{g_i})+(1+\exp(-((\mu_{iA^+}(\theta) - \mu_{iB})/\sigma_{g_i}\rho)))^{\rho}} d\theta \]
Two households that both consume 10 loads of laundry per month

<table>
<thead>
<tr>
<th>$j = B$</th>
<th>$j = A$ or $A^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_B = 1$</td>
<td>$\gamma_A = 1.25$</td>
</tr>
<tr>
<td>$\omega_B = 0.02$</td>
<td>$\omega_A = 0.016$</td>
</tr>
<tr>
<td>$kWh_B^* = 10$, $kWh_U^* = 490$</td>
<td>$kWh_A^* = 8$, $kWh_U^* = 490$</td>
</tr>
</tbody>
</table>

$$s_{ijt} = \left[ 1 + \omega_{ijt} (\gamma_j - 1) \right] kWh_{ijt}$$

$$s_B = (1 + 0.02 \cdot (1 - 1)) \cdot 500 = 500$$

$$s_A = (1 + 0.016 \cdot (1.25 - 1)) \cdot 498 = 500$$

Notes: One load of laundry is roughly 1 kWh if $j = B$. Both households therefore do 10 loads of laundry per month, and services produces by the other appliances are held fixed.
Appliance Price Variation
IV Electricity Price Elasticity Estimate

\[ \Delta \text{kWh}_{ij,2013} = \beta^s \Delta p^s_{ij,2013} + \omega_{ij,2013} \]

<table>
<thead>
<tr>
<th></th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>T-Stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Stage</td>
<td>0.214</td>
<td>0.016</td>
<td>13.1</td>
</tr>
<tr>
<td>IV Estimate</td>
<td>-939.1</td>
<td>91.4</td>
<td>-10.3</td>
</tr>
</tbody>
</table>

Elasticity at \( \bar{kWh}, \bar{p} \)

-0.246 .024 -10.3

Two-stage least squares regression and implied own-price elasticity of electricity consumption at the mean value of kWh and \( p^{kWh} \). The moment condition that defines \( \beta^s \) is \( p^{s,IV} \cdot \omega = 0 \). This is the same moment condition that’s imposed in the model, but the elasticity will be different because the model imposes additional moment restrictions and uses \( s \), not kWh. This allows households to endogenously respond to the price change by purchasing efficient washers.
### Washer Parameter Estimates

<table>
<thead>
<tr>
<th>Income Quintile</th>
<th>$\bar{\alpha}_i$</th>
<th>$\bar{\beta}^S$</th>
<th>$p^S$</th>
<th>Elasticity</th>
<th>$\tau$</th>
<th>$\kappa$</th>
<th>$\bar{\theta}_i$</th>
<th>$\sigma_\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>991.690</td>
<td>-1235.023</td>
<td>-0.661</td>
<td>273.397</td>
<td>322.818</td>
<td>-155.952</td>
<td>51.072</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(471.602)</td>
<td>(108.558)</td>
<td>(0.058)</td>
<td>(0.625)</td>
<td>(0.319)</td>
<td>(-2.177)</td>
<td>(0.172)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>975.936</td>
<td>-1006.677</td>
<td>-0.633</td>
<td>295.800</td>
<td>280.846</td>
<td>-165.797</td>
<td>67.535</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(489.986)</td>
<td>(90.318)</td>
<td>(0.057)</td>
<td>(0.513)</td>
<td>(0.300)</td>
<td>(-0.582)</td>
<td>(0.211)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1070.034</td>
<td>-1157.515</td>
<td>-0.567</td>
<td>93.641</td>
<td>380.414</td>
<td>-149.728</td>
<td>101.219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(523.641)</td>
<td>(98.989)</td>
<td>(0.049)</td>
<td>(10.282)</td>
<td>(3.677)</td>
<td>(-27.917)</td>
<td>(5.715)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>949.709</td>
<td>-1037.328</td>
<td>-0.564</td>
<td>139.245</td>
<td>352.297</td>
<td>-116.843</td>
<td>99.585</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(513.596)</td>
<td>(109.769)</td>
<td>(0.060)</td>
<td>(1.877)</td>
<td>(1.506)</td>
<td>(-1.208)</td>
<td>(0.312)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>692.155</td>
<td>-216.341</td>
<td>-0.132</td>
<td>62.125</td>
<td>382.654</td>
<td>-55.939</td>
<td>96.386</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(380.967)</td>
<td>(127.112)</td>
<td>(0.078)</td>
<td>(11.760)</td>
<td>(9.332)</td>
<td>(-26.881)</td>
<td>(3.917)</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** Standard errors reported in parentheses and the standard error of the price elasticity of demand for energy services in the third column was computed using the delta method. The parameter $\bar{\alpha}$ in the first column gives the mean of $\alpha_i$ for households in the given neighborhood income group. This is the average amount of energy services that households would consume if the price were 0. $\bar{\theta}$ is the mean of $\theta_i$ for households in this neighborhood income group, and I have assumed that $F_{g_i,\theta}(\theta)$ is exponentially distributed on the negative real numbers with parameter $\lambda_{g_i}$. 

Definition of Inframarginal

1. Claim rebate
2. Would have made same purchase w/out rebate

\[ Pr(V_{iA}^+ > V_{iA} > V_{iB}, V_{iC}) = \int_{-\text{Subsidy}}^{0} f_\theta(\theta) \cdot \frac{(1 + \exp(-(\mu_{iA} - \mu_{iB})/\rho))^{\rho-1}}{\exp(-\mu_{iA}) + (1 + \exp(-(\mu_{iA} - \mu_{iB})/\rho))^{\rho}} d\theta \]
Scope for Inframarginal Participation in the Data

Notes: Pie chart shows market shares conditional on purchase.
Total Program Effect (with Distortionary Price Change)

Expected total energy savings are given by

$$\Delta kWh^{TOT}_{\text{Fridge}} = -9,086 \text{kWh/Month}$$

$$= \sum_i \left( \sum_j Pr_{ij}(p^{A,75}, p^{S,75}) \cdot kWh_{ij}(p^{S,75}) \right)$$

$75 subsidy, revenue from electricity prices

$$- \sum_i \left( \sum_j Pr_{ij}(p^{A,0}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}) \right)$$

no subsidy, lower electricity prices

This accounts for change in adoption, as well as change in utilization given adoption.
Savings with Lump Sum Revenue Collection

Expected energy savings from capital upgrades are given by

\[
\Delta kWh^{Direct}_{\text{Fridge: } -262 \text{kWh/Month}} = \sum_i \left( \sum_j Pr_{ij}(p^{A,75}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}) \right) - \sum_i \left( \sum_j Pr_{ij}(p^{A,0}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}, \hat{\Omega}, W) \right)
\]

$75$ subsidy, revenue from lump sum tax

no subsidy

This accounts for change in adoption, as well as change in utilization given adoption.
Decomposing Participant and Non-participant Effects

Existing evaluations miss an important channel

- Treated and control customers in RCTs exposed to same $p^{S,50}$
- Energy price effect is 97% of total effect

\[
100 \cdot \frac{\Delta kWh^{TOT} - \Delta kWh^{Direct}}{\Delta kWh^{TOT}} = 97\%
\]
The plot shows residual electricity consumption from the difference-in-differences model $kWh_{it} = a_i + b_t + \text{Claimed Rebate}_{it} + e_{it}$ with household and month of sample fixed effects. Each point is the average of residual consumption in the treated group a given number of months from program participation. The average of the residuals in the control group is 0 by construction because of the included fixed effects.
### Difference-in-Differences Regression Table

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Levels</td>
<td>Logs</td>
<td>Levels</td>
<td>Logs</td>
</tr>
<tr>
<td>Participant x Post</td>
<td>-14.95</td>
<td>-0.0142</td>
<td>-12.57</td>
<td>-0.0106</td>
</tr>
<tr>
<td></td>
<td>(0.695)</td>
<td>(0.00109)</td>
<td>(1.466)</td>
<td>(0.00228)</td>
</tr>
<tr>
<td>YYMM FE</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>HER Recipients</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Observations</td>
<td>80104146</td>
<td>79895050</td>
<td>19474030</td>
<td>19425966</td>
</tr>
</tbody>
</table>

An observation is a household-month. Individual-level fixed effects are included in all specifications. The variable participant takes the value of 1 if a household claimed a washing machine rebate, 0 otherwise. Post takes the value of 1 for participant households in months after claiming rebate. Opower Home Energy Reports (HERs) affect usage and participation, so I have excluded recipients in the last two specifications. Standard errors are clustered by household.
## Selection into Program Participation

Table produced from a regression of each characteristic on a participation indicator. Standard errors are shown in parentheses. An observation is a household. Household income is the median household income in the household’s zipcode, which was gathered from the Census.

<table>
<thead>
<tr>
<th>Participant Status</th>
<th>0</th>
<th>1</th>
<th>Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly Income (1K Dollars)</td>
<td>5.6</td>
<td>6.3</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>(0.010)</td>
<td>(0.079)</td>
<td>(0.079)</td>
</tr>
<tr>
<td>Home Size (ft(^2))</td>
<td>1746.0</td>
<td>1775.5</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td>(45.397)</td>
<td>(358.225)</td>
<td>(361.090)</td>
</tr>
<tr>
<td>Home Age (Years)</td>
<td>34.4</td>
<td>32.0</td>
<td>-2.4</td>
</tr>
<tr>
<td></td>
<td>(0.085)</td>
<td>(0.673)</td>
<td>(0.678)</td>
</tr>
<tr>
<td>Daily Elec. Use (kWh)</td>
<td>22.8</td>
<td>24.4</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>(0.066)</td>
<td>(0.523)</td>
<td>(0.527)</td>
</tr>
<tr>
<td>Electricity Price (Dollars/kWh)</td>
<td>0.18</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>(0.00)</td>
<td>(0.00)</td>
<td>(0.00)</td>
</tr>
<tr>
<td>N</td>
<td>45,331</td>
<td>728</td>
<td></td>
</tr>
</tbody>
</table>