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

Chris Bruegge
Stanford University

November 2, 2017
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
An Important Energy Policy

Figure shows total nationwide 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 15x greater than benefits
2. Who benefits from the policies?
   ▶ Households in poorer zipcodes experience 1.5x greater loss of consumer surplus (in $)

Program Design
3. How can policy makers improve equity and efficiency?
   ▶ Lump sum fundraising and means-tested subsidy amounts
Non-distortionary Fundraising:

- Davis (2009), Fowlie et al. (2015), Houde and Aldy (2014), Houde and Aldy (2016)
- I show distortionary energy price change causes >80% of total energy savings

Local Effects, No Policy Design Implications

- I propose funding design that cuts deadweight loss by up to 70%
Economic Environment

- Two price changes, two choice margins
  1. Energy price -> energy consumption, appliance purchase
  2. Subsidy -> appliance purchase, energy consumption

Discrete - Continuous Model

- Links two related choice margins
Data and Estimation

Data
- Household-level program participation and electricity use
- Survey of appliance purchases (different sample of HHs)

Estimation
- Solve utility maximization problem
- GMM minimizes distance between model and data
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
- Program Design Counterfactual
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

No Purchase

J=C
Energy Star Purchasers Can Claim Rebate

J=A  J=A+  J=B  J=C

No Purchase

$50 REBATE
Households \((i)\) purchase appliances \((j)\) to consume services

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

- Energy Services e.g. clean laundry
- Energy Services per kWh
- Energy Input

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

\[
\max_{(j, s)} \quad n_{i0} + \xi_j(\theta_i) + \sigma g_i \epsilon_{ij} + \mathbb{E}_\nu \left[ \sum_t \delta^t \left( n_{it} + \frac{1}{2\beta s_{gi}} (s_{ijt} - \alpha - \nu_{ijt})^2 \right) \right]
\]

\text{Period 0 Purchase Utility}

\text{Expected PDV Future Operating Utility}

\text{s.t.} \quad l_{i0} \geq n_{i0} + p_{ij}^a,

\quad l_{it} \geq n_{it} + p_{ijt}^s \cdot s_{ijt}, \quad t \in \{1, \ldots, 120\}.

\text{Choice Variables}

- \textbf{\textit{j:} Appliance choice}
- \textbf{\textit{s:} Energy service consumption}
- \textbf{\textit{n:} Numeraire}
### Description of Discrete Choice Fixed Effects

<table>
<thead>
<tr>
<th>Discrete Choice</th>
<th>$\xi_j(\theta_i)$</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>$\epsilon_iC$</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>$\epsilon_iB$</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$\epsilon_iA$</td>
<td></td>
</tr>
<tr>
<td>A$^+$</td>
<td>$\epsilon_iA$</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

\[
\max_{(j, s)} \left\{ n_{i0} + \xi_j(\theta_i) + \epsilon_{ij} \right\} + \mathbb{E}_\nu \left[ \sum_t \delta^t \left( n_{it} + \frac{1}{2\beta_g} (s_{ijt} - \alpha_i - \nu_{ijt})^2 \right) \right]
\]

Period 0 Purchase Utility

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

s.t.

Expected PDV Future Operating Utility

Choice Variables

- \( j \): Appliance choice
- \( s \): Energy service consumption
- \( n \): Numeraire
Error Accounting

\[ E_\nu[U(j, \bar{s})] = n_{i0} + \xi_j(\theta_i) + \epsilon_{ij} + E_\nu \left[ \sum_t \delta_t \left( n_{it} + \frac{1}{2\beta_{s_{gi}}} (s_{ijt} - \alpha_i - \nu_{ijt})^2 \right) \right] \]

Structural Error Terms

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

Stationary environment with respect to

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

- Utility Maximization Problem
  - Discrete Choice / Continuous Choice
    - Optimal Energy Consumption and Appliance Choices
- Data / Identification
- Program Evaluation Results
- Program Design Counterfactual
Realization of $\nu$ after purchase

$$\max_{\tilde{s}} \quad U(\tilde{s}|j)$$

subject to $$l_{it} \geq n_{it} + p_{ij}^s \cdot s_{ijt}, \quad t \in \{1, \ldots, 120\}.$$ 

Optimal Energy Service Consumption

$$s_{ijt}^* = \alpha_i + \beta_{gi}^s p_{ijt}^s + \nu_{ijt}$$
Expected Conditional Indirect Utility

\[ V_{ij} = E_\nu \left[ U(s_{ijt}^*; j, \bar{\epsilon}_i, \theta_i, \nu_{ijt}) \right] \]

Optimal Appliance Choice

\[ Pr_{ij} = Pr(V_{ij} > \max(V_{ik}), j \neq k) \]

\[ = \int \int dF_\epsilon dF_\theta \]

\[ \{\bar{\epsilon}_i, \theta_i: V_{ij} > \max(V_{ik}), j \neq k \} \]
Similarities to Nested Logit

Choices $A^+$ and $A$ are exactly the same Energy Star appliance

$$V_{iA^+} = l_{i0} - p_{iA}^a + \tau g_i + \kappa g_i + E_{\nu} [V^*(p_{iA}^s)] + \epsilon_{iA} + \theta_i + \text{Subsidy}$$

Changes basic structure of nested logit

$$Pr_{iA^+} = Pr(V_{iA^+} > V_{iA}, V_{iA^+} > V_{iB}, V_{iC})$$

$$= Pr(\text{Subsidy} + \theta_i > 0, V_{iA^+} > V_{iB}, V_{iC})$$

Not Logit, Nested Logit
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><strong>2013 Program Participation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_i(A^+) \text{ Washer}$</td>
<td>84,020</td>
<td>0.018</td>
<td>0.13</td>
</tr>
<tr>
<td>$I_i(A^+) \text{ Fridge}$</td>
<td>84,020</td>
<td>0.004</td>
<td>0.06</td>
</tr>
</tbody>
</table>

**Monthly HH Energy Use (kWh)**

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<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 $Pr_{(A^+)^c}$

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>
</tbody>
</table>

N: 1,088 84,020

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

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

Moment Conditions

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

- 1 kWh = 1 unit of energy services if \( j = B \)

Define \( \omega_{ijt} \) as the share of total electricity used by appliance \( j \) in month \( t \). Total energy service consumption is

\[
\begin{align*}
  s_{ijt} &= \gamma_j \cdot \omega_{ijt} \cdot kWh_{it} + (1 - \omega_{ijt}) kWh_{it} \\
  &= \left[ 1 + \omega_{ijt}(\gamma_j - 1) \right] kWh_{it}
\end{align*}
\]
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.
Identifying $\sigma_\epsilon \text{ corr}(\rho^a, I) \ I(A)$ over Time

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 $= \beta_{g_i} \cdot \frac{p^s}{s}$. 
The plot shows the simulated empirical distribution of $\theta_{gi} = \lambda_{gi} \cdot Rayleigh(1)$. 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
Kaldor-Hicks Economic Efficiency

“Total Surplus” includes

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

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

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

<table>
<thead>
<tr>
<th>Non-distortionary</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Charge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Savings (kWh)</td>
<td>10,610</td>
<td>60,114</td>
</tr>
<tr>
<td>Social Cost of 1 kWh ($)</td>
<td>.1</td>
<td>.1</td>
</tr>
<tr>
<td>Environmental Benefit ($)</td>
<td>1,061.00</td>
<td>6,011.40</td>
</tr>
</tbody>
</table>

Notes: Energy savings represent in the first column represent the present discounted value of lifetime energy savings from households whose durable purchase was marginal to the subsidy. In the second column, savings increase because of one year of higher prices needed to fund one program year. 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.
“Total Surplus” includes

- Size of the environmental externality
- **Consumer surplus**
  - Distortion to utilization because of $\Delta p^{kWh}$
  - Hassle cost of rebate application
  - Appliance purchase cost
- 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></th>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Consumer Surplus ($)</td>
<td>-63,987</td>
<td>-75,646</td>
<td>0.846</td>
</tr>
<tr>
<td>+ Environmental Benefit</td>
<td>1,061.00</td>
<td>6,011.40</td>
<td>0.177</td>
</tr>
<tr>
<td><strong>Net Welfare Change ($)</strong></td>
<td>-62,926</td>
<td>-69,635</td>
<td>0.904</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that producer surplus is zero (i.e. the appliance market is competitive) and that the disutility \( \theta \) of filling out a rebate application is a real economic cost. These assumptions will be relaxed in the next slides.
Consumer Surplus with Appliance Market Failures

\[ V_j = l_0 - p_j^a + \xi_j(\theta) + \sigma \epsilon_j + \Gamma \cdot \mathbb{E}_\nu \left[ \sum_t \delta^t (l_t - p_j^s (\frac{1}{2} \beta^s p_j^S + \alpha + \nu_{jt})) \right] \]

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>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Welfare Change ($)</strong></td>
<td>-62,926</td>
<td>-69,635</td>
<td>0.904</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Change in Consumer Surplus ($)</strong></td>
<td>-63,570</td>
<td>-103,860</td>
<td>0.612</td>
</tr>
<tr>
<td>+ Environmental Benefit</td>
<td>1,061.00</td>
<td>6,011.40</td>
<td>0.177</td>
</tr>
<tr>
<td><strong>Net Welfare Change ($)</strong></td>
<td>-62,509</td>
<td>-97,853</td>
<td>0.639</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that producer surplus is zero (i.e. the appliance market is competitive) and that the disutility $\theta$ of filling out a rebate application is a real economic cost. These assumptions will be relaxed in the next slides.
Kaldor-Hicks Economic Efficiency

“Total Surplus” includes

- Size of the environmental externality
- **Consumer surplus**
  - Distortion to utilization because of $\Delta p^{kWh}$
  - Hassle cost of rebate application
  - Appliance purchase cost
- Producer surplus
Hassle Costs in the Utility Function

\[ V_{A^+} = I_0 - p_{A^+}^a + \tau + \kappa + \theta^* + \sigma \epsilon_j + \]

\[ \mathbb{E}_\nu \left[ \sum_t \delta^t (l_t - p_j^S (\frac{1}{2} \beta^S p_{A^+}^S + \alpha + \nu_{jt})) \right] \]

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 A: 25% Undervaluation of Consumption Utility</th>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Welfare Change ($)</td>
<td>-62,509</td>
<td>-97,853</td>
<td>0.639</td>
</tr>
</tbody>
</table>

| Panel B: 25% Undervaluation, $\theta^* = 0$ | Non-distortionary Fixed Charge | Distortionary $\Delta p^{kWh}$ | Ratio |
| Change in Consumer Surplus ($\) | -14,144 | -54,434 | 0.260 |
| + Environmental Benefit | 1,061.00 | 6,011.40 | 0.177 |
| Net Welfare Change ($\) | -13,083 | -48,422 | 0.270 |

Notes: Net welfare calculations in this table assume that producer surplus is zero (i.e. the appliance market is competitive). The parameter $\theta^* = \theta$ enters the decision utility, but is a “mistake” rather than a real economic cost; in the experience utility, $\theta^* = 0$. 
Expected Marginal vs. Inframarginal Participation

<table>
<thead>
<tr>
<th>Program Participation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(\text{Marginal Participants})$</td>
</tr>
<tr>
<td>$E(\text{Inframarginal Participants})$</td>
</tr>
<tr>
<td>$E(\text{Total Participants})$</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.
“Total Surplus” includes

- Size of the environmental externality
- Consumer surplus
- Producer surplus
  - Regulated utility companies earn no economics profits
  - Appliance Producer Surplus
### Enviro. and Appliance Mkt. Failures, $\theta^* = 0$, $PS > 0$

<table>
<thead>
<tr>
<th></th>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in Consumer Surplus ($)</td>
<td>-14,144</td>
<td>-54,434</td>
<td>0.260</td>
</tr>
<tr>
<td>Change in Producer Surplus ($)</td>
<td>50,207</td>
<td>50,268</td>
<td>0.999</td>
</tr>
<tr>
<td>+ Environmental Benefit</td>
<td>1,061.00</td>
<td>6,011.40</td>
<td>0.177</td>
</tr>
<tr>
<td><strong>Net Welfare Change ($)</strong></td>
<td>37,124</td>
<td>1,846</td>
<td>20.1123</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that households discount consumption utility by a factor of .25 at the time of purchase, that the disutility $\theta$ of filling out a rebate application is zero, and that 50% of the price difference between the Energy Star and the traditional appliance represents producer surplus.
Roadmap

- Utility Maximization Problem
- Data / Identification
- Program Evaluation Results
  - Parameter Estimates
  - Economic Efficiency
  - Distributional Equity
- Program Design Counterfactual
## Consumer Surplus by Neighborhood Income Quintile

<table>
<thead>
<tr>
<th>Non-distortionary Fixed Charge</th>
<th>Distortionary $\Delta p^{kWh}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1$</td>
<td>-0.87</td>
</tr>
<tr>
<td>$g_2$</td>
<td>-0.82</td>
</tr>
<tr>
<td>$g_3$</td>
<td>-0.83</td>
</tr>
<tr>
<td>$g_4$</td>
<td>-0.58</td>
</tr>
<tr>
<td>$g_5$</td>
<td>-0.71</td>
</tr>
</tbody>
</table>

Notes: Net welfare calculations in this table assume that producer surplus is zero (i.e. the appliance market is competitive) and that the disutility $\theta$ of filling out a rebate application is a real economic cost.
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 Income Quintile</th>
<th>Subsidy ($)</th>
<th>Fixed Fee (per HH · Year)</th>
<th>ΔCS (per HH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.00</td>
<td>1.72</td>
<td>3.60</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>1.72</td>
<td>-1.72</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>1.72</td>
<td>-1.72</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>1.72</td>
<td>-1.72</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
<td>1.72</td>
<td>-1.72</td>
</tr>
</tbody>
</table>

| 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 means-tested point of sale policy if the regulator valued producer surplus the same as consumer surplus.
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 Savings From Electricity Price Increases

\[
\text{% Savings Per Customer / Month} = \underbrace{0.52\%}_{\text{Price Elasticity}} \cdot \underbrace{-0.16}_{\text{Price Change}} \cdot \underbrace{3.3\%}_{\text{Price Change}}
\]

Estimates of the Price Elasticity

- Ito (2014): -0.08
- Reiss et al (2005): -0.39
- This paper: -.16
Savings Per Participant = \frac{\text{Savings per Customer / Month}}{\text{Marginal Participants}} \times \text{Share of Participants}

% Savings Per Customer / Month = 0.013\%

Estimates of the Share of Marginal Participants

- Boomhower and Davis (2014): 50%
- Houde and Aldy (2014): 8%
- This paper: 3%
## Energy Price Distortions Dominate

<table>
<thead>
<tr>
<th>% Savings / Household · Month</th>
<th>Appliance Channel</th>
<th>Energy Price Channel</th>
<th>Energy Price % of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conservative</strong></td>
<td>0.125</td>
<td>0.5</td>
<td>79.4%</td>
</tr>
<tr>
<td><strong>Midrange</strong></td>
<td>0.013</td>
<td>1.0</td>
<td>98.7%</td>
</tr>
<tr>
<td><strong>High</strong></td>
<td>0.001</td>
<td>2.5</td>
<td>&gt;99.9%</td>
</tr>
<tr>
<td><strong>My Estimate</strong></td>
<td>~</td>
<td>~</td>
<td>97.8%</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

$\bar{U}$ Indifference Curve

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

Estimable Equations

- No washing machine purchase \((j=D)\)
  
  \[ V_{iD} = I_i + V^*(p^s_{iD}, X_i) + \epsilon_{iD} \]

  \(p^s = \) 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 ($j=A$)
No washing machine purchase (j=D)

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

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

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

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

\[
F_{g_i, \theta} = \exp(\lambda g_i \theta)
\]

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

\[
Pr_{iA} = \int_{-\text{Subsidy}}^{0} f_{g_i, \theta}(\theta) \cdot \frac{(1+\exp(-((\mu_{iA}(\theta) - \mu_iC)/\sigma_{gi})/\rho))^{\rho-1}}{\exp(-\mu_{iA}(\theta)/\sigma_{gi})+(1+\exp(-((\mu_{iA}(\theta) - \mu_iC)/\sigma_{gi})/\rho))^{\rho}} \, d\theta
\]
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>

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

\[s_B = (1 + .02 \cdot (1 - 1)) \cdot 500 = 500\]

\[s_A = (1 + .016 \cdot (1.25 - 1)) \cdot 498 = 500\]

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.
IV Electricity Price Elasticity Estimate

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

<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 \( k\overline{Wh}, \overline{p} \)

-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>$\beta^S$</th>
<th>$\rho^S$</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

\[
\Delta kWh^{TOT}_{\text{Fridge}} = \sum_i \left( \sum_j Pr_{ij}(p^{A,75}, p^{S,75}) \cdot kWh_{ij}(p^{S,75}) \right) - \sum_i \left( \sum_j Pr_{ij}(p^{A,0}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}) \right)
\]

$75$ subsidy, revenue from electricity prices

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

\[
\Delta \text{kWh}^{\text{Direct}} = \sum_{i} \left( \sum_{j} Pr_{ij}(p^{A,75}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}) \right) - \sum_{i} \left( \sum_{j} Pr_{ij}(p^{A,0}, p^{S,0}) \cdot kWh_{ij}(p^{S,0}, \hat{\Omega}, W) \right)
\]

Fridge: $\text{−262kWh/Month}$

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.
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.
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.