Eliciting Private User Information for Residential Demand Response

D.P. Zhou, M. Balandat, M.A. Dahleh, and C.J. Tomlin

[datong.zhou, balandat, tomlin]@berkeley.edu, dahleh@mit.edu

December 12, 2017

Incentive Design and Sharing Economy

Incentive Design and Sharing Economy

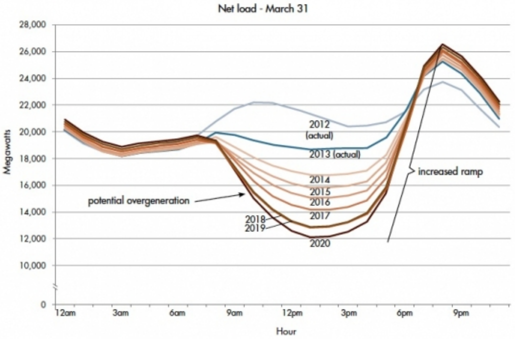
Incentive Design and Sharing Economy

Incentive Design and Sharing Economy

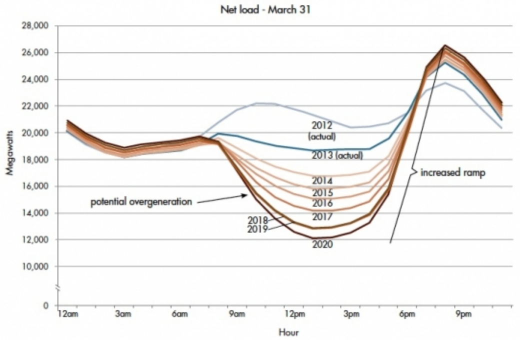
Incentive Design and Sharing Economy

Incentive Design and Sharing Economy

Incentive Design and Sharing Economy

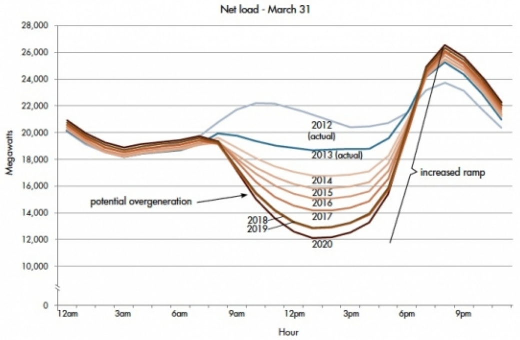


Incentive Design and Sharing Economy



Wholesale Market

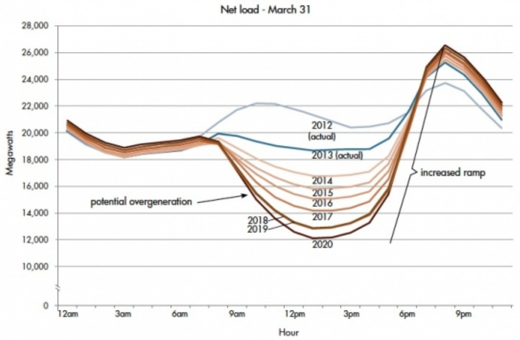
Incentive Design and Sharing Economy



Wholesale Market

Electric Utility

Incentive Design and Sharing Economy

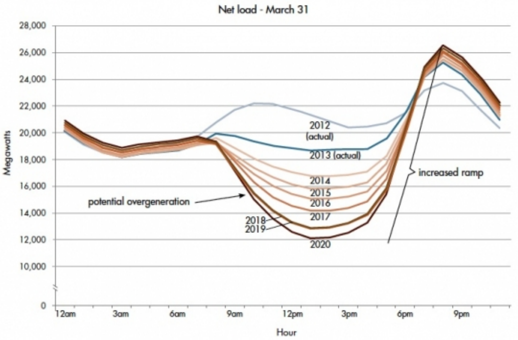


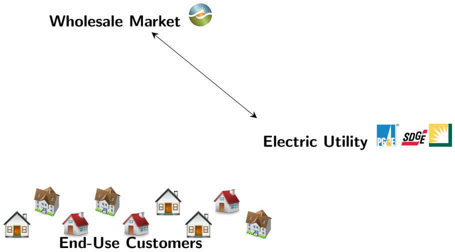
Wholesale Market

Electric Utility

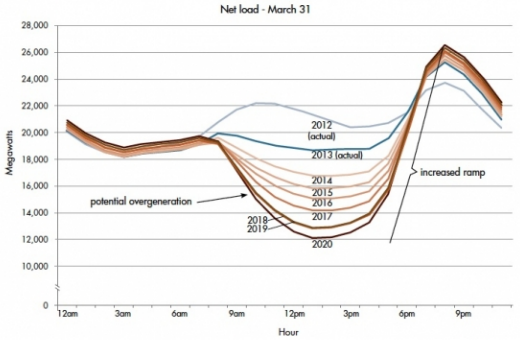
End-Use Customers

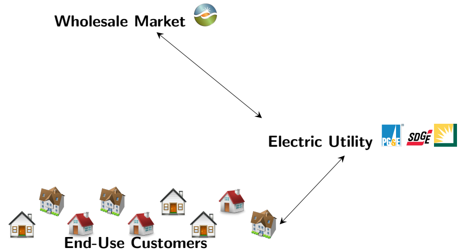
Incentive Design and Sharing Economy



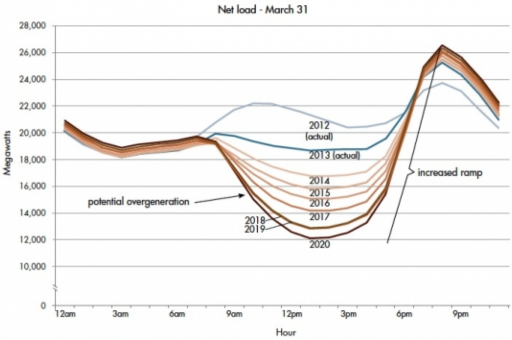


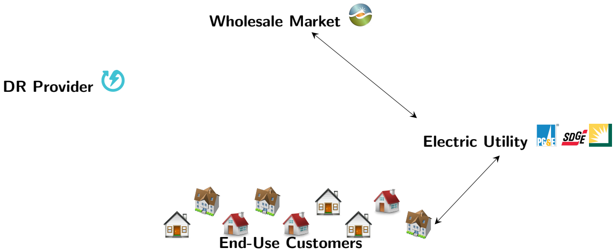
Incentive Design and Sharing Economy



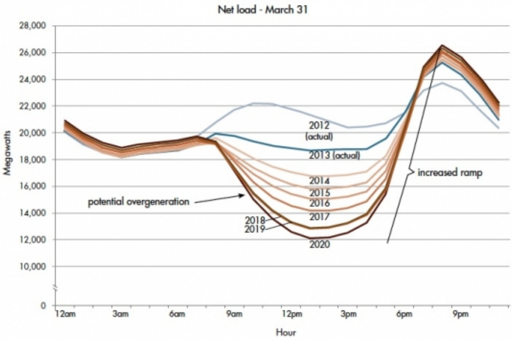


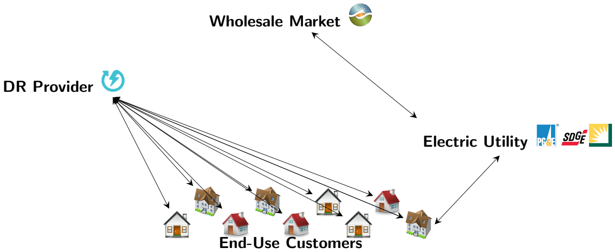
Incentive Design and Sharing Economy



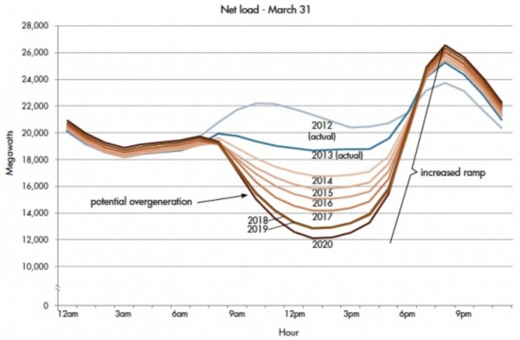


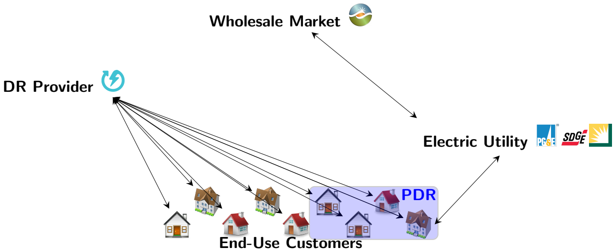
Incentive Design and Sharing Economy



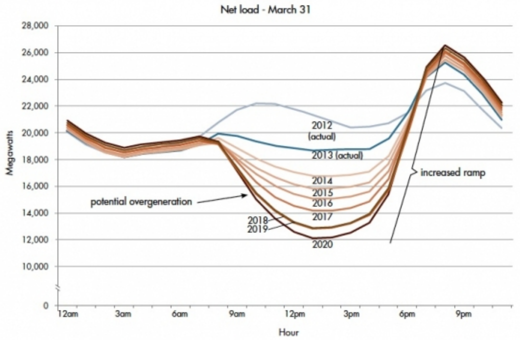


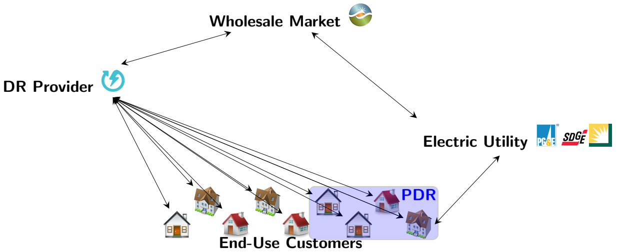
Incentive Design and Sharing Economy



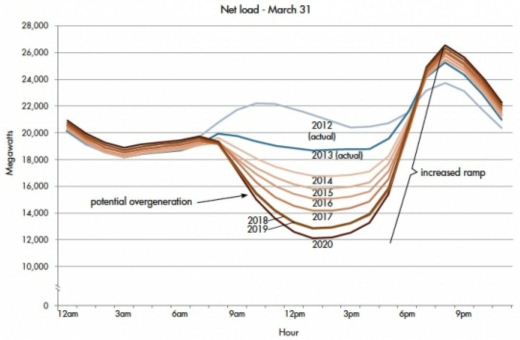


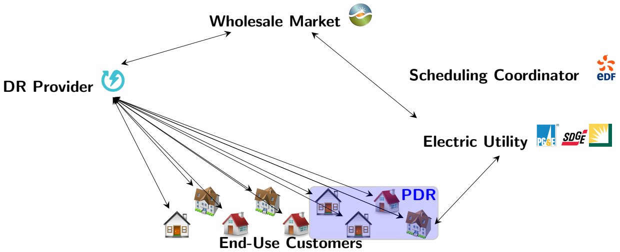
Incentive Design and Sharing Economy



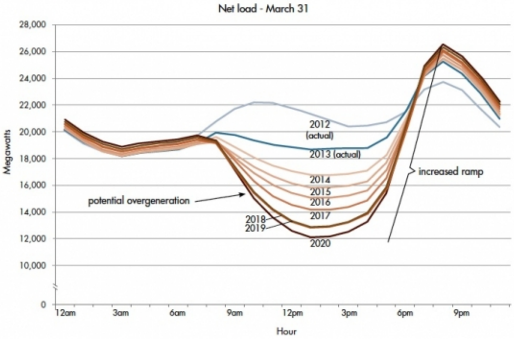


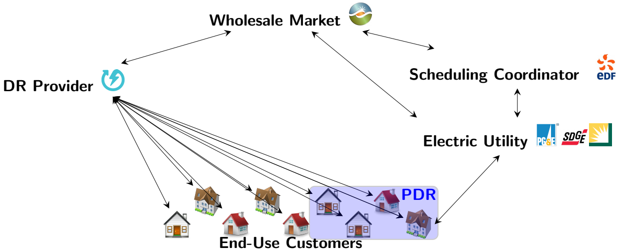
Incentive Design and Sharing Economy



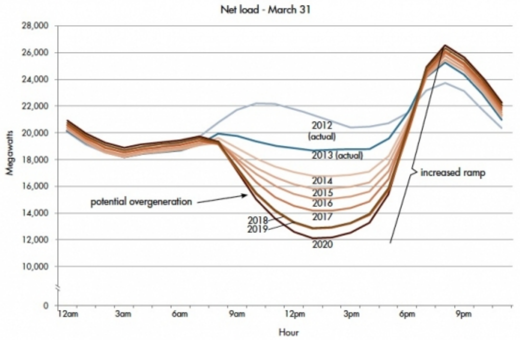


Incentive Design and Sharing Economy



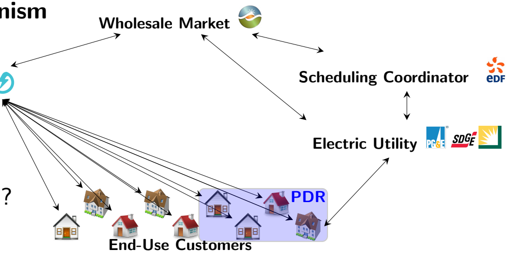


Incentive Design and Sharing Economy



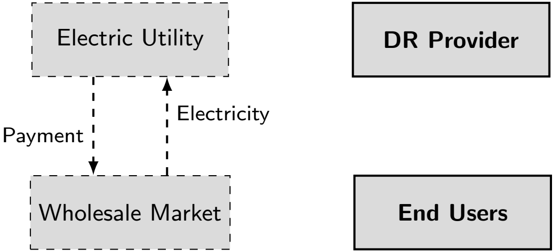
Demand Response Auction Mechanism

- DR Provider ⇔ User Interaction?

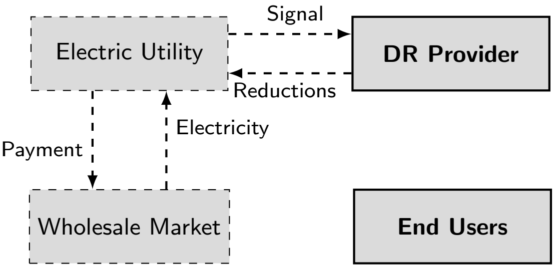


Interaction between Market Participants

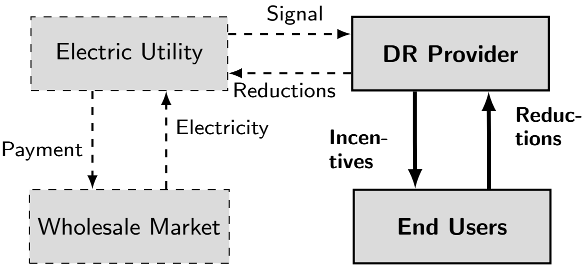
Interaction between Market Participants



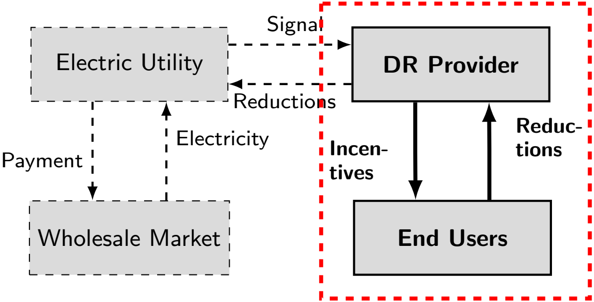
Interaction between Market Participants



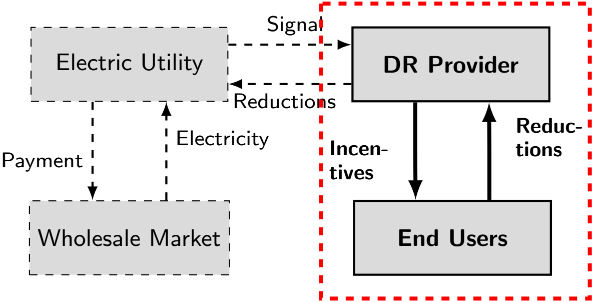
Interaction between Market Participants



Interaction between Market Participants



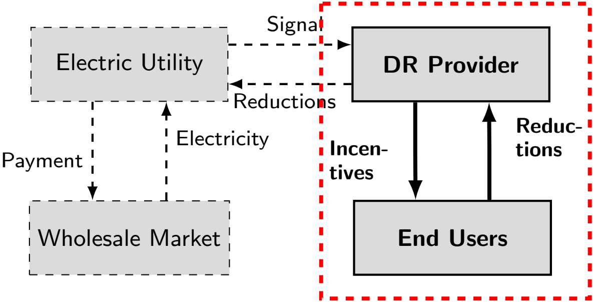
Interaction between Market Participants



(Residential) Demand Response

- DR Provider seeks to collect "reductions" of electricity consumption from its customers under contract in exchange for monetary incentives

Interaction between Market Participants



(Residential) Demand Response

- DR Provider seeks to collect "reductions" of electricity consumption from its customers under contract in exchange for monetary incentives

Challenges

- How can reduction be measured?
- How heterogeneous are users in their reduction behavior?
- Can users "game" the system by misreporting their preferences?

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = \left(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+\right)\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\ldots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = \left(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+\right)\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\ldots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = \left(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+\right)\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\dots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = \left(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+\right)\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\dots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = (r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+)\,\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\dots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\dots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = \left(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+\right)\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\ldots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

DR Provider and End Users

End Users

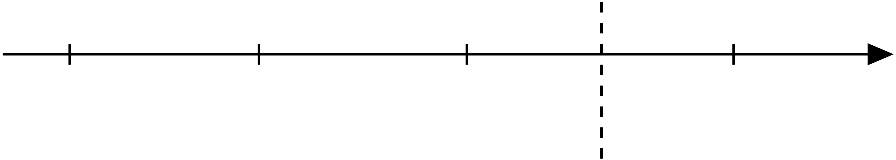
- Each user $i \in \mathcal{I}$ has *estimated* baseline consumption $\hat{x}_i \in \mathbb{R}_+$ and actual, materialized consumption $x_i \in \mathbb{R}_+$
- Estimated reduction is $\delta_i = (\hat{x}_i - x_i)\mathbf{1}_{i \in \mathcal{T}}$
- Demand curve / price elasticity of demand: $x_i(r_i) = \bar{x}_i \exp(-\alpha_i r_i)$
- User i's utility function: $u_i = (r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+)\,\mathbf{1}_{i \in \mathcal{T}}$

DR Provider

$$\begin{aligned} \underset{r_1,\ldots,r_n}{\text{minimize}} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i \left(r_i \mathbf{1}_{\delta_i < 0} - q_i \mathbf{1}_{\delta_i \geq 0}\right)\right] \\ \text{subject to} \quad & \mathbb{E}_{\delta_1,\ldots,\delta_n}\left[\sum\nolimits_{i \in \mathcal{I}} \delta_i\right] \geq M. \end{aligned}$$

- Incentivize subset of end-users $\mathcal{T} \subset \mathcal{I}$ with user-specific, per-unit rewards $\{r_i \in \mathbb{R}_+ \mid i \in \mathcal{T}\}$
- Charge user i per-unit penalty $q_i \in \mathbb{R}_+$ for *increasing* consumption
- Collect $M \in \mathbb{R}_+$ units of aggregate reduction while minimizing payment to users:

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$

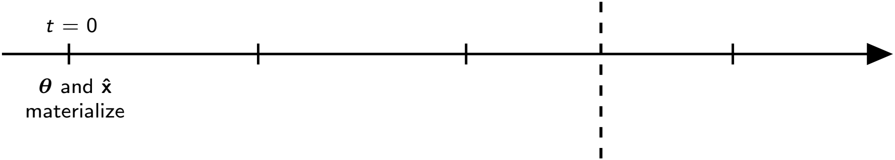
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I}, \ \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I}, \ \mathbf{z} \in \boldsymbol{\Theta}$

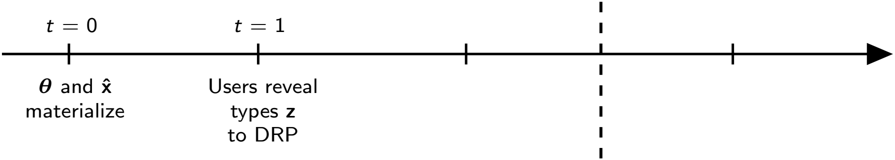
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$

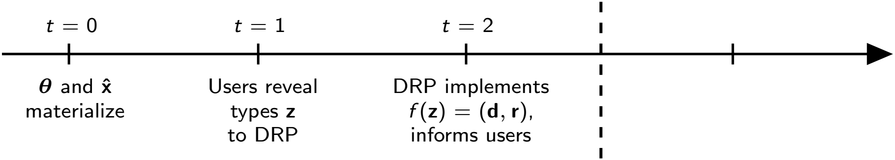
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$

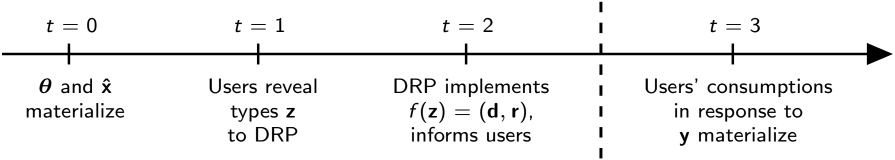
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I}, \; \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i} [u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)] \quad \forall i \in \mathcal{I}, \; \mathbf{z} \in \boldsymbol{\Theta}$

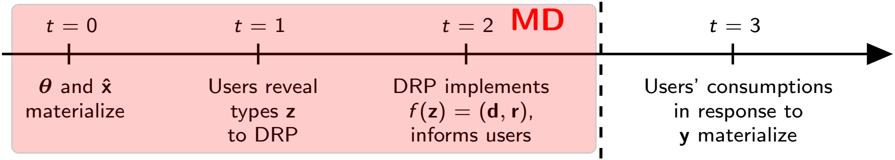
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Setup



At $t = 0$:

- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
    - Elasticity α_i characterizes willingness to reduce
    - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization

At $t = 1$:

- *Individual Rationality*: $\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$
- *Incentive Compatibility*: $\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$

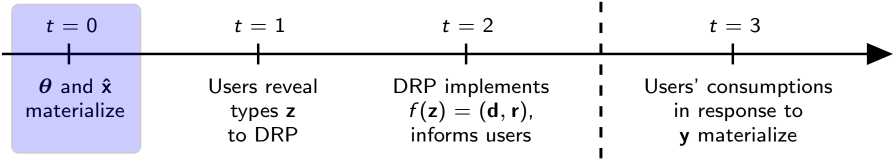
At $t = 2$:

- Social choice function $f(\mathbf{z})$ consists of allocation and payment rule

At $t = 3$:

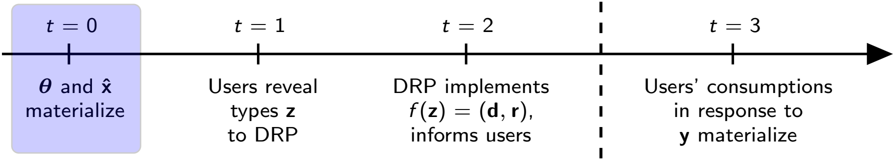
- Settlements between DR Provider and users
- *But: Not considered in Mechanism Design*

Mechanism Design, $t = 0$

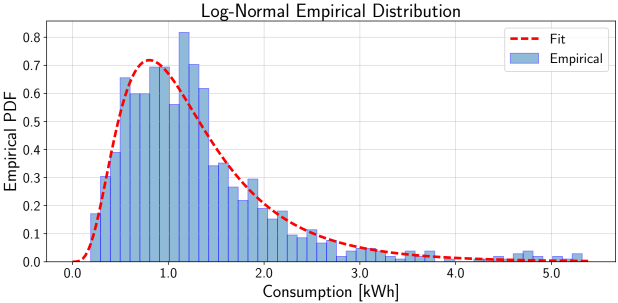


- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization
- Fit F and G from smart meter data in California

Mechanism Design, $t = 0$

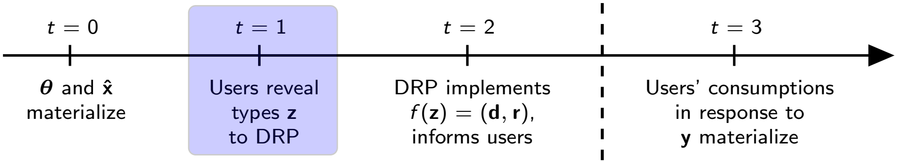


- User i's type is $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$
  - Elasticity α_i characterizes willingness to reduce
  - Base consumption $\bar{x}_i$ is stochastic, does not follow rational profit-maximization
- Fit F and G from smart meter data in California



$$\bar{x}_i \sim \mathrm{Lognormal}(\sigma, s, \ell)$$
$$\sigma \sim \mathcal{N}(\mu_n, \sigma_n)$$
$$s \sim \mathrm{Cauchy}(\ell_c, s_c)$$
$$\ell \sim \mathrm{Exponential}(\lambda_e)$$

Mechanism Design, $t = 1$



Dominant Strategy Equilibrium (DSE)

$$\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$$

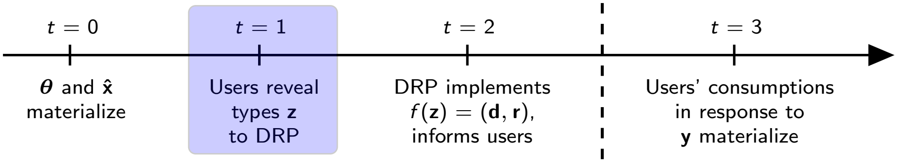
- Revelation Principle: Given a DSE, focus on *direct* mechanisms → Users report their type truthfully $\mathbf{z}_i = \boldsymbol{\theta}_i$

Individual Rationality Constraints

- Expected payoff (user's utility) must be larger than any outside option:

$$\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq \underbrace{\mathbb{E}[(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+)\mathbf{1}_{i \notin \mathcal{T}}]}_{=\text{utility if not targeted}} = 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$$

Mechanism Design, $t = 1$



Dominant Strategy Equilibrium (DSE)

$$\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$$

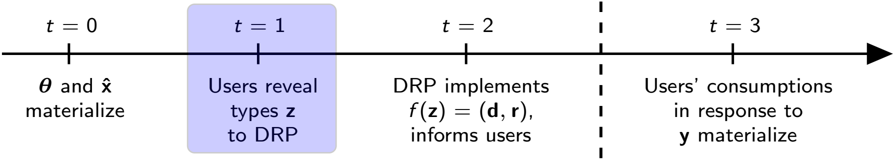
- Revelation Principle: Given a DSE, focus on *direct* mechanisms $\rightarrow$ Users report their type truthfully $\mathbf{z}_i = \boldsymbol{\theta}_i$

Individual Rationality Constraints

- Expected payoff (user's utility) must be larger than any outside option:

$$\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq \underbrace{\mathbb{E}[(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+)\mathbf{1}_{i \notin \mathcal{T}}]}_{=\text{utility if not targeted}} = 0 \quad \forall i \in \mathcal{I},\ \mathbf{z} \in \boldsymbol{\Theta}$$

Mechanism Design, $t = 1$



Dominant Strategy Equilibrium (DSE)

$$\boldsymbol{\theta}_i = \arg\max_{\mathbf{z}_i \in \boldsymbol{\Theta}_i} \mathbb{E}_{\mathbf{z}_i}\left[u_i(f(\mathbf{z}_i, \mathbf{z}_{-i}), \boldsymbol{\theta}_i)\right] \quad \forall i \in \mathcal{I}, \; \mathbf{z} \in \boldsymbol{\Theta}$$

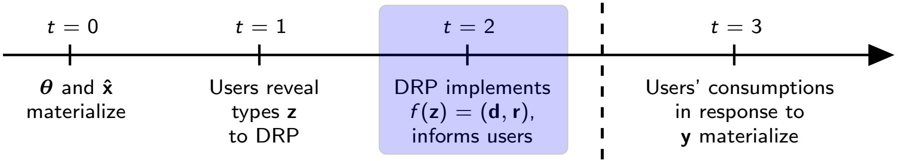
- Revelation Principle: Given a DSE, focus on *direct* mechanisms $\rightarrow$ Users report their type truthfully $\mathbf{z}_i = \boldsymbol{\theta}_i$

Individual Rationality Constraints

- Expected payoff (user's utility) must be larger than any outside option:

$$\mathbb{E}[u_i(f(\boldsymbol{\theta}_i, \mathbf{z}_{-i}))] \geq \underbrace{\mathbb{E}[(r_i[\hat{x}_i - x_i]_+ - q_i[x_i - \hat{x}_i]_+)\,\mathbf{1}_{i \notin \mathcal{T}}]}_{=\text{utility if not targeted}} = 0 \quad \forall i \in \mathcal{I}, \; \mathbf{z} \in \boldsymbol{\Theta}$$

Mechanism Design, $t = 2$



Social Choice Function

- $f(\boldsymbol{\theta}) : \boldsymbol{\Theta} \mapsto \mathcal{Y}$ maps type $\boldsymbol{\theta}$ to collective choice $\mathbf{y} = (\mathbf{d}, \mathbf{r}) \in \mathcal{Y} = \{0,1\}^n \times \mathbb{R}_+^n$
  - Vector of allocation decisions $\mathbf{d} \in \{0,1\}^n$
  - Vector of rewards $\mathbf{r} \in \mathbb{R}_+^n$

VCG-Style Mechanism

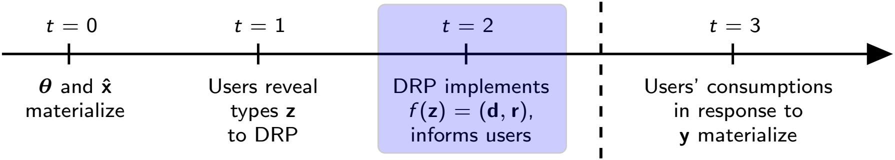
- Let $\mu_i(d_i = 1, r_i) = \int_{\mathbb{R}_+} u_i(\alpha_i, r_i, x)\, dG_{\xi_i}(x)$ denote user i's expected utility, given reward r_i. Let $\tilde{r}_i$ denote the unique r_i such that $\mu_i(d_i = 1, \tilde{r}_i) = 0$.

$$j_{\max} = \min_j \left\{ j \in \mathbb{N}_+ \;\middle|\; \sum_{i=1}^{j} \delta_i(\tilde{r}_j | \boldsymbol{\theta}_i) \geq M \right\}$$

$$j(i) = \min_k \left\{ k \in \mathbb{N}_+ \;\middle|\; \sum_{s=1, s \neq i}^{k} \delta_s(\tilde{r}_k | \boldsymbol{\theta}_s) \geq M \right\} \qquad \forall\, i \in \{1, \dots, j_{\max}\} =: \mathcal{T}$$

$$r_i \leftarrow \tilde{r}_{j(i)} \geq \tilde{r}_i \quad \forall\, i \in \mathcal{T}$$

Mechanism Design, $t = 2$



Social Choice Function

- $f(\boldsymbol{\theta}) : \boldsymbol{\Theta} \mapsto \mathcal{Y}$ maps type $\boldsymbol{\theta}$ to collective choice $\mathbf{y} = (\mathbf{d}, \mathbf{r}) \in \mathcal{Y} = \{0,1\}^n \times \mathbb{R}^n_+$
  - Vector of allocation decisions $\mathbf{d} \in \{0,1\}^n$
  - Vector of rewards $\mathbf{r} \in \mathbb{R}^n_+$

VCG-Style Mechanism

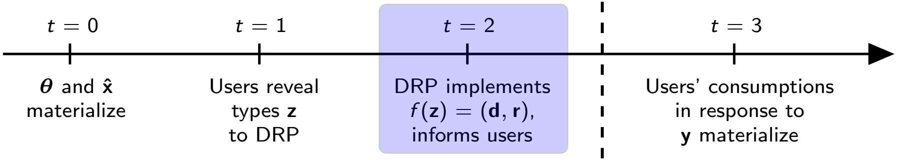
- Let $\mu_i(d_i = 1, r_i) = \int_{\mathbb{R}_+} u_i(\alpha_i, r_i, x) \; dG_{\boldsymbol{\xi}_i}(x)$ denote user i's expected utility, given reward r_i. Let $\tilde{r}_i$ denote the unique r_i such that $\mu_i(d_i = 1, \tilde{r}_i) = 0$.

$$j_{\max} = \min_j \left\{ j \in \mathbb{N}_+ \;\middle|\; \sum_{i=1}^{j} \delta_i(\tilde{r}_j | \boldsymbol{\theta}_i) \geq M \right\}$$

$$j(i) = \min_k \left\{ k \in \mathbb{N}_+ \;\middle|\; \sum_{s=1, s \neq i}^{k} \delta_s(\tilde{r}_k | \boldsymbol{\theta}_s) \geq M \right\} \qquad \forall\, i \in \{1, \ldots, j_{\max}\} =: \mathcal{T}$$

$$r_i \leftarrow \tilde{r}_{j(i)} \geq \tilde{r}_i \quad \forall\, i \in \mathcal{T}$$

Mechanism Design, $t = 2$



Social Choice Function

- $f(\boldsymbol{\theta}) : \boldsymbol{\Theta} \mapsto \mathcal{Y}$ maps type $\boldsymbol{\theta}$ to collective choice $\mathbf{y} = (\mathbf{d}, \mathbf{r}) \in \mathcal{Y} = \{0,1\}^n \times \mathbb{R}_+^n$
  - Vector of allocation decisions $\mathbf{d} \in \{0,1\}^n$
  - Vector of rewards $\mathbf{r} \in \mathbb{R}_+^n$

VCG-Style Mechanism

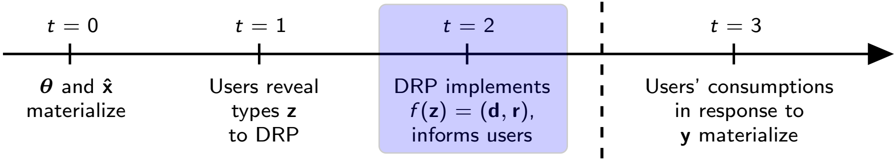
- Let $\mu_i(d_i = 1, r_i) = \int_{\mathbb{R}_+} u_i(\alpha_i, r_i, x)\ dG_{\boldsymbol{\xi}_i}(x)$ denote user i's expected utility, given reward r_i. Let $\tilde{r}_i$ denote the unique r_i such that $\mu_i(d_i = 1, \tilde{r}_i) = 0$.

$$j_{\max} = \min_j \left\{ j \in \mathbb{N}_+ \;\middle|\; \sum_{i=1}^{j} \delta_i(\tilde{r}_j | \boldsymbol{\theta}_i) \geq M \right\}$$

$$j(i) = \min_k \left\{ k \in \mathbb{N}_+ \;\middle|\; \sum_{s=1, s \neq i}^{k} \delta_s(\tilde{r}_k | \boldsymbol{\theta}_s) \geq M \right\} \qquad \forall\, i \in \{1, \ldots, j_{\max}\} =: \mathcal{T}$$

$$r_i \leftarrow \tilde{r}_{j(i)} \geq \tilde{r}_i \quad \forall\, i \in \mathcal{T}$$

Mechanism Design, $t = 2$



Social Choice Function

- $f(\boldsymbol{\theta}) : \boldsymbol{\Theta} \mapsto \mathcal{Y}$ maps type $\boldsymbol{\theta}$ to collective choice $\mathbf{y} = (\mathbf{d}, \mathbf{r}) \in \mathcal{Y} = \{0, 1\}^n \times \mathbb{R}_+^n$
  - Vector of allocation decisions $\mathbf{d} \in \{0, 1\}^n$
  - Vector of rewards $\mathbf{r} \in \mathbb{R}_+^n$

VCG-Style Mechanism

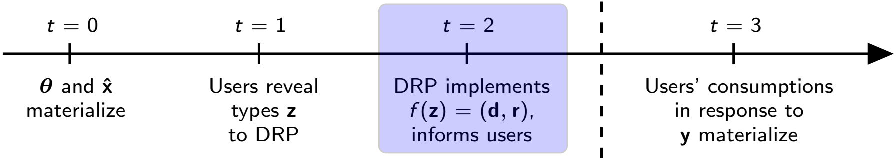
- Let $\mu_i(d_i = 1, r_i) = \int_{\mathbb{R}_+} u_i(\alpha_i, r_i, x) \; dG_{\boldsymbol{\xi}_i}(x)$ denote user i's expected utility, given reward r_i. Let $\tilde{r}_i$ denote the unique r_i such that $\mu_i(d_i = 1, \tilde{r}_i) = 0$.

$$j_{\max} = \min_j \left\{ j \in \mathbb{N}_+ \;\middle|\; \sum_{i=1}^{j} \delta_i(\tilde{r}_j | \boldsymbol{\theta}_i) \geq M \right\}$$

$$j(i) = \min_k \left\{ k \in \mathbb{N}_+ \;\middle|\; \sum_{s=1, s \neq i}^{k} \delta_s(\tilde{r}_k | \boldsymbol{\theta}_s) \geq M \right\} \qquad \forall\; i \in \{1, \ldots, j_{\max}\} =: \mathcal{T}$$

$$r_i \leftarrow \tilde{r}_{j(i)} \geq \tilde{r}_i \quad \forall\; i \in \mathcal{T}$$

Mechanism Design, $t = 2$



Social Choice Function

- $f(\boldsymbol{\theta}) : \boldsymbol{\Theta} \mapsto \mathcal{Y}$ maps type $\boldsymbol{\theta}$ to collective choice $\mathbf{y} = (\mathbf{d}, \mathbf{r}) \in \mathcal{Y} = \{0,1\}^n \times \mathbb{R}_+^n$
  - Vector of allocation decisions $\mathbf{d} \in \{0,1\}^n$
  - Vector of rewards $\mathbf{r} \in \mathbb{R}_+^n$

VCG-Style Mechanism

- Let $\mu_i(d_i = 1, r_i) = \int_{\mathbb{R}_+} u_i(\alpha_i, r_i, x)\; dG_{\boldsymbol{\xi}_i}(x)$ denote user i's expected utility, given reward r_i. Let $\tilde{r}_i$ denote the unique r_i such that $\mu_i(d_i = 1, \tilde{r}_i) = 0$.

$$j_{\max} = \min_j \left\{ j \in \mathbb{N}_+ \;\middle|\; \sum_{i=1}^{j} \delta_i(\tilde{r}_j | \boldsymbol{\theta}_i) \geq M \right\}$$

$$j(i) = \min_k \left\{ k \in \mathbb{N}_+ \;\middle|\; \sum_{s=1, s\neq i}^{k} \delta_s(\tilde{r}_k | \boldsymbol{\theta}_s) \geq M \right\} \qquad \forall\, i \in \{1, \ldots, j_{\max}\} =: \mathcal{T}$$

$$r_i \leftarrow \tilde{r}_{j(i)} \geq \tilde{r}_i \quad \forall\, i \in \mathcal{T}$$

Simulations

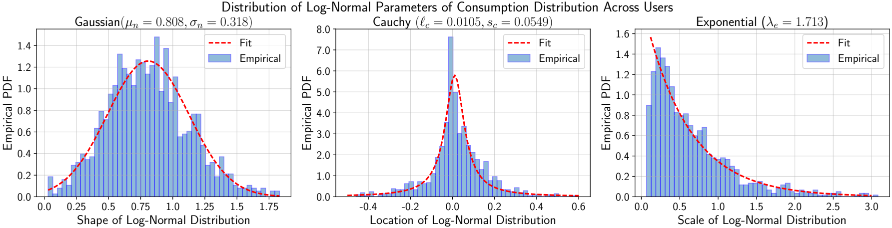
- Recall: $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$, G lognormal
- G is parameterized by *shape, location, scale* parameters:

- Draw user types from hierarchical model
- $n = 500$ users, $q = 5.0$, $\alpha_i \sim \text{unif}[0.05, 0.06]$
- Comparison to omniscient DR Provider

Omniscient DR Provider does not give up *information rent*

Simulations

- Recall: $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$, G lognormal
- G is parameterized by *shape, location, scale* parameters:

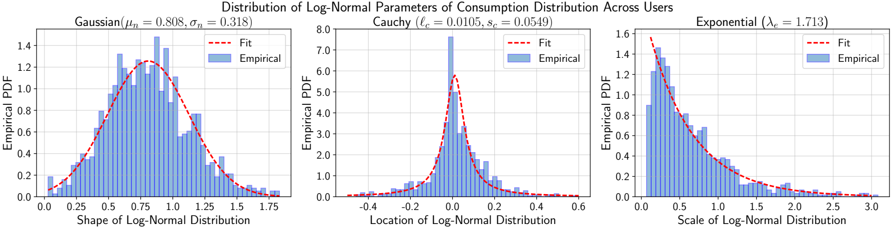


- Draw user types from hierarchical model
- $n = 500$ users, $q = 5.0$, $\alpha_i \sim \text{unif}[0.05, 0.06]$
- Comparison to omniscient DR Provider

Omniscient DR Provider does not give up *information rent*

Simulations

- Recall: $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$, G lognormal
- G is parameterized by *shape, location, scale* parameters:

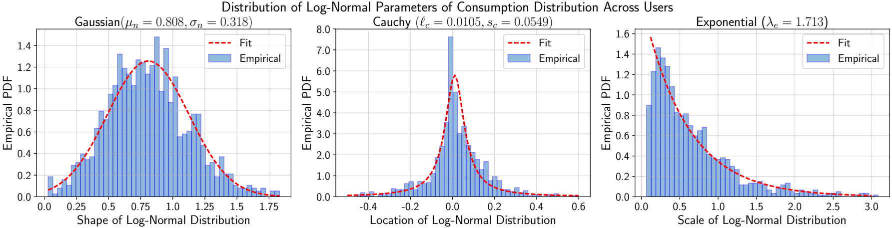


- Draw user types from hierarchical model
- $n = 500$ users, $q = 5.0$, $\alpha_i \sim \text{unif}[0.05, 0.06]$
- Comparison to omniscient DR Provider

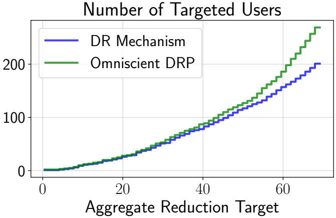
Omniscient DR Provider does not give up *information rent*

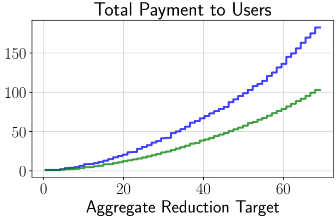
Simulations

- Recall: $\boldsymbol{\theta}_i = (\alpha_i \sim F_\alpha, \boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}})$, where $\bar{x}_i \sim G_{\boldsymbol{\xi}_i} \sim G_{\boldsymbol{\xi}_i \sim F_{\boldsymbol{\xi}}}$, G lognormal
- G is parameterized by *shape, location, scale* parameters:



- Draw user types from hierarchical model
- $n = 500$ users, $q = 5.0$, $\alpha_i \sim \text{unif}[0.05, 0.06]$
- Comparison to omniscient DR Provider





Omniscient DR Provider does not give up *information rent*

Virtual Reductions from Baseline Inaccuracies

Fundamental Problem of Causal Inference[1]

- Either the outcome under treatment or under control is observed, but not both
- That is, the counterfactual consumption is always unobserved
- $\hat{x}_i$ is an estimate of the counterfactual, prone to estimation inaccuracies

CAISO 10-in-10 Baseline[2]

- Calculate $\hat{x}_i$ as the mean of the 10 previous consumptions
- Reduction Components: $\delta_i = (\hat{x}_i - \bar{x}_i) + \bar{x}_i(1 - e^{-\alpha_i r_i}) =: \delta_i^{\mathrm{BL}} + \delta_i^r$
- *Virtual Reductions* due to variance in $\hat{x}_i$ estimation

[1] P. W. Holland. "Statistics and Causal Inference". In: *Journal of the American Statistical Association* 81.396 (1986), pp. 945–960.

[2] *California Independent System Operator Corporation (CAISO): Fifth Replacement FERC Electric Tariff.* 2014.

Virtual Reductions from Baseline Inaccuracies

Fundamental Problem of Causal Inference[1]

- Either the outcome under treatment or under control is observed, but not both
- That is, the counterfactual consumption is always unobserved
- $\hat{x}_i$ is an estimate of the counterfactual, prone to estimation inaccuracies

CAISO 10-in-10 Baseline[2]

- Calculate $\hat{x}_i$ as the mean of the 10 previous consumptions
- Reduction Components: $\delta_i = (\hat{x}_i - \bar{x}_i) + \bar{x}_i(1 - e^{-\alpha_i r_i}) =: \delta_i^{\mathrm{BL}} + \delta_i^r$
- *Virtual Reductions* due to variance in $\hat{x}_i$ estimation

[1] P. W. Holland. "Statistics and Causal Inference". In: *Journal of the American Statistical Association* 81.396 (1986), pp. 945–960.

[2] *California Independent System Operator Corporation (CAISO): Fifth Replacement FERC Electric Tariff.* 2014.

Virtual Reductions from Baseline Inaccuracies

Fundamental Problem of Causal Inference[1]

- Either the outcome under treatment or under control is observed, but not both
- That is, the counterfactual consumption is always unobserved
- $\hat{x}_i$ is an estimate of the counterfactual, prone to estimation inaccuracies

CAISO 10-in-10 Baseline[2]

- Calculate $\hat{x}_i$ as the mean of the 10 previous consumptions
- Reduction Components: $\delta_i = (\hat{x}_i - \bar{x}_i) + \bar{x}_i(1 - e^{-\alpha_i r_i}) =: \delta_i^{\mathrm{BL}} + \delta_i^{r}$
- *Virtual Reductions* due to variance in $\hat{x}_i$ estimation

[1] P. W. Holland. "Statistics and Causal Inference". In: *Journal of the American Statistical Association* 81.396 (1986), pp. 945–960.

[2] *California Independent System Operator Corporation (CAISO): Fifth Replacement FERC Electric Tariff.* 2014.

Virtual Reductions from Baseline Inaccuracies

Fundamental Problem of Causal Inference[1]

- Either the outcome under treatment or under control is observed, but not both
- That is, the counterfactual consumption is always unobserved
- $\hat{x}_i$ is an estimate of the counterfactual, prone to estimation inaccuracies

CAISO 10-in-10 Baseline[2]

- Calculate $\hat{x}_i$ as the mean of the 10 previous consumptions
- Reduction Components: $\delta_i = (\hat{x}_i - \bar{x}_i) + \bar{x}_i(1 - e^{-\alpha_i r_i}) =: \delta_i^{\mathrm{BL}} + \delta_i^r$
- *Virtual Reductions* due to variance in $\hat{x}_i$ estimation

[1] P. W. Holland. "Statistics and Causal Inference". In: *Journal of the American Statistical Association* 81.396 (1986), pp. 945–960.

[2] *California Independent System Operator Corporation (CAISO): Fifth Replacement FERC Electric Tariff.* 2014.

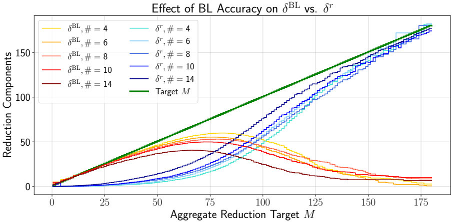
Virtual Reductions from Baseline Inaccuracies

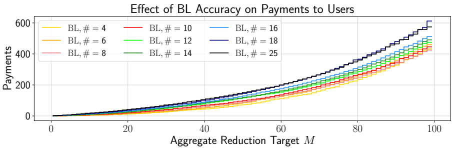
Fundamental Problem of Causal Inference[1]

- Either the outcome under treatment or under control is observed, but not both
- That is, the counterfactual consumption is always unobserved
- $\hat{x}_i$ is an estimate of the counterfactual, prone to estimation inaccuracies

CAISO 10-in-10 Baseline[2]

- Calculate $\hat{x}_i$ as the mean of the 10 previous consumptions
- Reduction Components: $\delta_i = (\hat{x}_i - \bar{x}_i) + \bar{x}_i(1 - e^{-\alpha_i r_i}) =: \delta_i^{\mathrm{BL}} + \delta_i^r$
- *Virtual Reductions* due to variance in $\hat{x}_i$ estimation





[1] P. W. Holland. "Statistics and Causal Inference". In: *Journal of the American Statistical Association* 81.396 (1986), pp. 945–960.

[2] *California Independent System Operator Corporation (CAISO): Fifth Replacement FERC Electric Tariff.* 2014.

Conclusion

Summary

- Modeled Residential Demand Response in Mechanism Design framework
- Intercept and slope of demand curve are users' private information
- DR Provider elicits private information with incentive compatible auction
- Practical Issue: "Baseline Gaming"

Future Work

- Improve baseline estimates (counterfactuals)
- Analyze serial correlation of consumption time series
- Extend one-shot problem to online, sequential auctions

THANK YOU!
QUESTIONS?