A Contract for Demand Response based on Probability of Call

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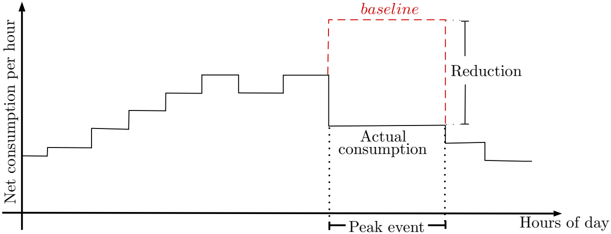
Outline

Introduction: drawbacks of baseline estimation

Traditional incentive-based DR programs require an estimated baseline against which consumer's load reduction is measured.
The current methods for establishing baseline: i) averaging techniques, ii) regression approaches, etc.

- Incentive payment = (Reduction) x (Reward/kWh)
- Reduction = Baseline - Observed



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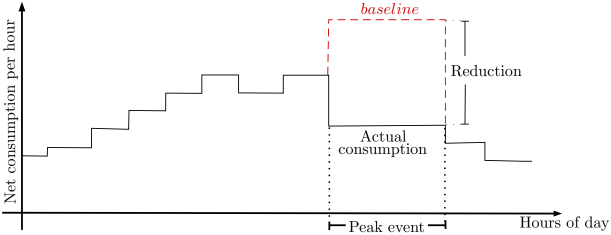

Problem:

- Baseline manipulation (Severin Borenstein, 2014; Vuelvas and Ruiz, 2017; Chao, 2011).

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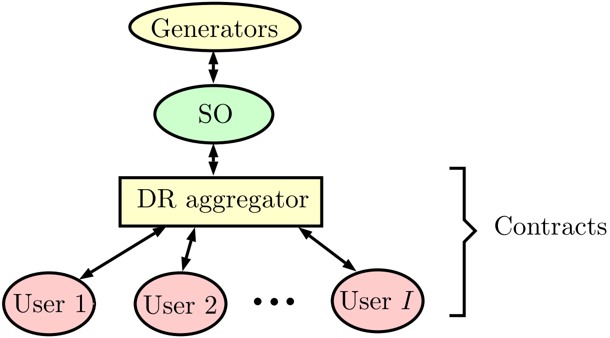
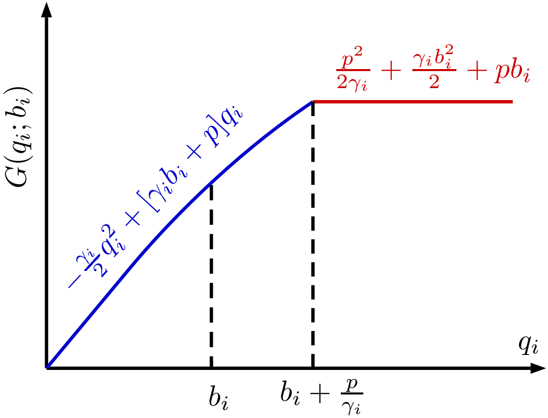
- Consumer self reports his baseline (it is not estimated).
- Agents bid information in terms of energy (baseline and reduction capacity).
- In this model, the main objective of the aggregator is to select randomly which participant consumers are called to perform DR.



Consumer model

- Utility function: $G(q_i \text{ (consumption) }; b_i\text{(baseline)}) \longrightarrow$ Customer satisfaction function.



Parameters:

γ_i: marginal utility (energy preference)

p: energy price

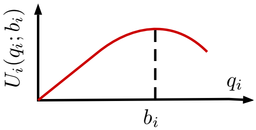
b_i: baseline

Variable:

q_i: actual consumption

Problem Setting

- The energy price p is given.
- The energy total cost is $\pi_i(q_i) = pq_i$
- The payoff function without DR is defined as
  $U_i(q_i; b_i) = G(q_i; b_i) - \pi_i(q_i)$
- b_i is the rational decision (optimal solution) of $U_i(q_i; b_i)$



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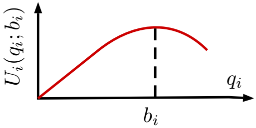

- Let p_2 be the rebate price. E.g. the incentive could be $p_2(\hat{b}_i - q_i)_+$. The superscript ^ means declared information.
- $\hat{q}_i$ is reported energy consumption under DR.
- r_i is a binary variable that indicates if user i is called to participate in DR.

Contract and consumer's problem (1/2)

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4.	Consumers decide q_i	(demand response event)

Questions: What is the declared information that maximizes the consumer benefit? What is the uncertainty that user faces?

Contract and consumer's problem (2/2)

Let $\pi_{i,3}^{r_i}(\hat{b}_i, \hat{q}_i, q_i)$ be the new aggregator payment scheme:

$$\pi_{i,3}^{r_i}(\hat{b}_i, \hat{q}_i, q_i) = \begin{cases} p \max(\hat{b}_i,\, q_i) & r_i = 0 \text{ (non-called)} \\ pq_i - p_2(\hat{b}_i - q_i)_+ + p_2 \left| q_i - \hat{q}_i \right| & r_i = 1 \text{ (called)} \end{cases}$$

- $p \max(\hat{b}_i,\, q_i)$: buy the baseline or pay the consumption
- pq_i: energy cost
- $p_2(\hat{b}_i - q_i)_+$: incentive payment
- $p_2 \left| q_i - \hat{q}_i \right|$: deviation penalty

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The optimization problem:

$$[\hat{b}_i^{\,*}, \hat{q}_i^{\,*}, q_i^*] = \underset{\hat{b}_i, \hat{q}_i, q_i \in \{0, q_{max,i}\}}{\arg\max} \quad J_i = \mathbf{E}\left(G(q_i; b_i) - \pi_{i,3}^{r_i}(\hat{b}_i, \hat{q}_i, q_i)\right)$$

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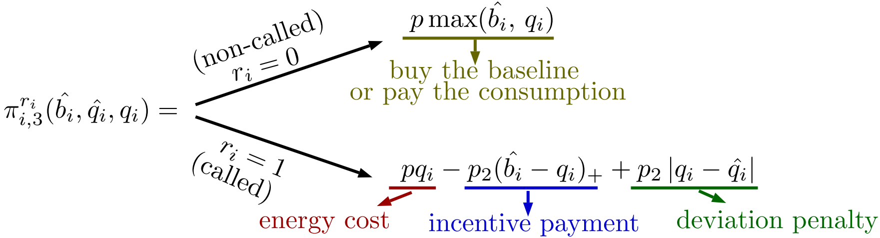

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The contract is settled as a two-stage procedure:

Stage 1) Given the prices p and p_2, each consumer reports $\hat{b}_i$ and $\hat{q}_i$ to aggregator.

Stage 2) Aggregator determines which users are called by means of the variable r_i. Each agent decides his actual energy consumption q_i.

Consumer optimal behavior

When not called for the DR event, the optimal user response, given his previous declared information, is described by the following theorem:

Theorem

The optimal consumption q^*_{i,r_i} for the signal $r_i = 0$ of a participant consumer in the proposed contract is:

$$q^*_{i,r_i=0} = \begin{cases} b_i & 0 \leq \hat{b}_i \leq b_i \qquad \textit{strategy } \mathcal{A} \\ \hat{b}_i & b_i < \hat{b}_i \leq b_i + p/\gamma_i \qquad \textit{strategy } \mathcal{B} \\ b_i + p/\gamma_i & b_i + p/\gamma_i < \hat{b}_i \leq q_{max,i} \qquad \textit{strategy } \mathcal{C} \end{cases}$$

Consumer optimal behavior

When called for the DR event, the optimal user response, given his previous declared information, is described by the following theorem:

Theorem

The optimal consumption q^*_{i,r_i} for the signal $r_i = 1$ of a participant consumer in the proposed contract is:

$$q^*_{i,r_i=1} = \begin{cases} b_i & b_i \le \hat{b}_i \le q_{max,i}, b_i \le \hat{q}_i \le \hat{b}_i \le q_{max,i} & \text{strategy } \mathcal{U} \\ \hat{q}_i & b_i - \frac{p_2}{\gamma_i} \le \hat{b}_i \le q_{max,i}, b_i - \frac{2p_2}{\gamma_i} \le \hat{q}_i \le \hat{b}_i \le b_i & \text{strategy } \mathcal{V} \\ \hat{q}_i & \alpha \le \hat{b}_i \le b_i - \frac{p_2}{\gamma_i}, b_i - \frac{2p_2}{\gamma_i} \le \hat{q}_i \le b_i - \frac{p_2}{\gamma_i} & \text{strategy } \mathcal{W} \\ (b_i - \frac{p_2}{\gamma_i})_+ & b_i - \frac{2p_2}{\gamma_i} \le \hat{b}_i \le \alpha, b_i - \frac{2p_2}{\gamma_i} \le \hat{q}_i \le \hat{b}_i \le b_i - \frac{p_2}{\gamma_i} & \text{strategy } \mathcal{X} \\ (b_i - \frac{p_2}{\gamma_i})_+ & 0 \le \hat{b}_i \le b_i - \frac{3p_2}{2\gamma_i}, 0 \le \hat{q}_i \le \hat{b}_i \le b_i - \frac{2p_2}{\gamma_i} & \text{strategy } \mathcal{Y} \\ (b_i - \frac{2p_2}{\gamma_i})_+ & b_i - \frac{3p_2}{2\gamma_i} \le \hat{b}_i \le q_{max,i}, 0 \le \hat{q}_i \le b_i - \frac{2p_2}{\gamma_i} & \text{strategy } \mathcal{Z} \end{cases}$$

with $\alpha = \frac{\gamma_i b_i^2}{2p_2} - \frac{\gamma_i b_i \hat{q}_i}{p_2} - b_i + \frac{\gamma_i \hat{q}_i{}^2}{2p_2} + 2\hat{q}_i + \frac{p_2}{2\gamma_i}.$

Consumer optimal behavior

Knowing the optimal consumer responses to the random signal r_i, the best strategy in the first stage is to report the baseline and reduction level of the following theorem:

Theorem

Given q^*_{i,r_i} from Theorems 1 and 2, then the optimal reports $\hat{b_i}^*$ and $\hat{q}_i{}^*$ are:

$$\hat{b_i}^* = \begin{cases} \frac{p_{r_i} p_2}{\gamma_i (1-p_{r_i})} + b_i & 0 \leq p_{r_i} \leq \frac{p}{p_2+p} \\ q_{max,i} & \frac{p}{p_2+p} \leq p_{r_i} \leq 1 \end{cases}$$

$$\hat{q}_i{}^* = \left(b_i - \frac{p_2}{\gamma_i} \right)_+$$

Consumer optimal behavior

A user decides to participate in the program if his profit (net benefit) is greater, or at least equal, to what he gets when not participating. From the previous theorems, the expected profit of the consumer is:

Collorary

The optimal expected profit J^* is:

$$J_i^* = \begin{cases} \frac{b_i^2\gamma_i}{2} + \frac{p_{r_i} p_2^2}{2\gamma_i(1-p_{r_i})} & 0 \le p_{r_i} \le \frac{p}{p_2+p} \\ \frac{p^2}{2\gamma_i} + b_i p - p q_{max,i} + \frac{b_i^2\gamma_i}{2} - \frac{p^2 p_{r_i}}{2\gamma_i} + \frac{p_2^2 p_{r_i}}{2\gamma_i} & \\ -b_i p_{r_i} - b_i p_2 p_{r_i} + p q_{max,i} p_{r_i} + p_2 q_{max,i} p_{r_i} & \frac{p}{p_2+p} \le p_{r_i} \le 1 \end{cases}$$

Contract properties

- Individually rational (voluntary participation): a user that participates in this approach obtains a profit at least as good as he does not signing the DR contract.
- Incentive compatibility on the reported energy consumption under DR: a consumer informs the truthful consumption under DR according to his preferences.
- Asymptotic incentive compatibility on the reported baseline: as the probability of call tends to zero, the consumer's optimal strategy is to declare $\hat{b}_i = b_i$.

Numerical case study

$$[\hat{b_i}^*, \hat{q_i}^*, q_i^*] = \overbrace{\arg\max \quad J_i = \mathbf{E}(G(q_i; b_i) - \pi_{i,3}^{r_i}(\hat{b_i}, \hat{q_i}, q_i))}^{\text{Consumer's decision problem}}$$

- q_i^* → actual consumption
- $\hat{q_i}^*$ → declared reduction capacity
- $\hat{b_i}^*$ → reported baseline

What are the consumer's optimal decisions under this DR contract?

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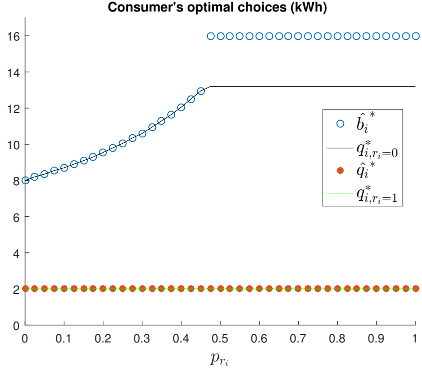
Simulation info:

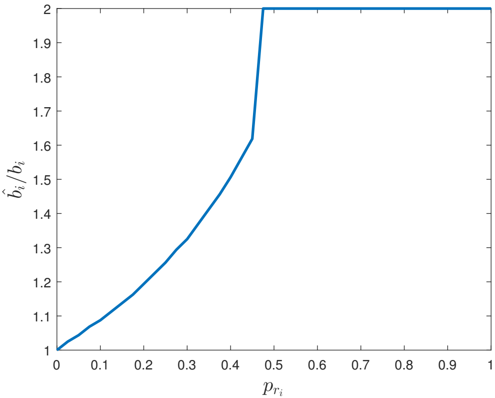
- The retail price is $p = 0.26$ \$/kWh.
- True baseline is $b_i = 8$ kWh.
- The incentive/penalty price is $p_2 = 0.3$ \$/kWh.
- The marginal utility is $\gamma_i = 0.05$ \$/kWh^2.
- The maximum allowable consumption is $q_{max,i} = 16$ kWh.
- A Monte Carlo simulation is performed with 1000 realizations of r_i for each value of probability.

Results: optimal consumer's choice (p_{r_i} is the probability of call)



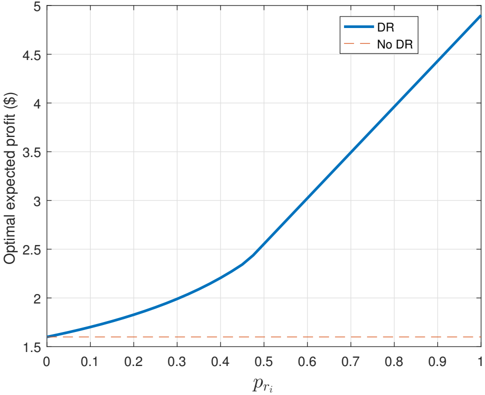
- Aggregator should call for DR to users with a probability of call between zero and the threshold one to limit gaming opportunities (asymptotic truthfulness for baseline).
- An agent declares what he is willing to reduce according to his true preferences $\hat{q}_i{}^* = q^*_{i,r_i=1}$ irrespective of the probability of call.

Results: Percentage of gaming limitation on the reported baseline (p_{r_i} is the probability of call)



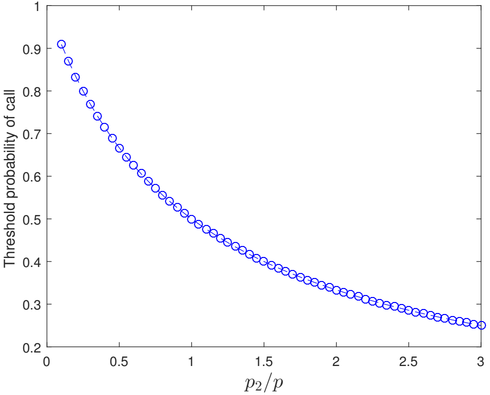
- For instance, an aggregator calls a group of agents with a probability of call equals to $p_{r_i} = 0.1$ then rational consumers have incentives to overreport the baseline by an 11%.

Results: Optimal expected profit of a consumer (p_{r_i} is the probability of call).



- The user's benefit when he participates in this contract is at least as good as when he does not join in the incentive-based DR program (voluntary participation).

Results: Threshold probability of call (p_{r_i} is the probability of call)



- If $p = p_2$, the critical point is 0.5 of likelihood.
- The threshold probability is designed by the aggregator through the selection of prices.

Conclusions

- DR contract was proposed which induces voluntary participation and truthfulness based on the probability of call.
- The main goal of the aggregator is to call a subset of users that meets the probability criterion.
- A contract for incentive-based DR based on probability of call enables to limit the gaming opportunities.
- Advantages: no computation by aggregator, information exchange in terms of energy, easy to understand by agents, implementable.

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