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Contract Design for Service Reliability Management based on Demand-Side Flexibility

The Case of Power Reliability Demand Response Program

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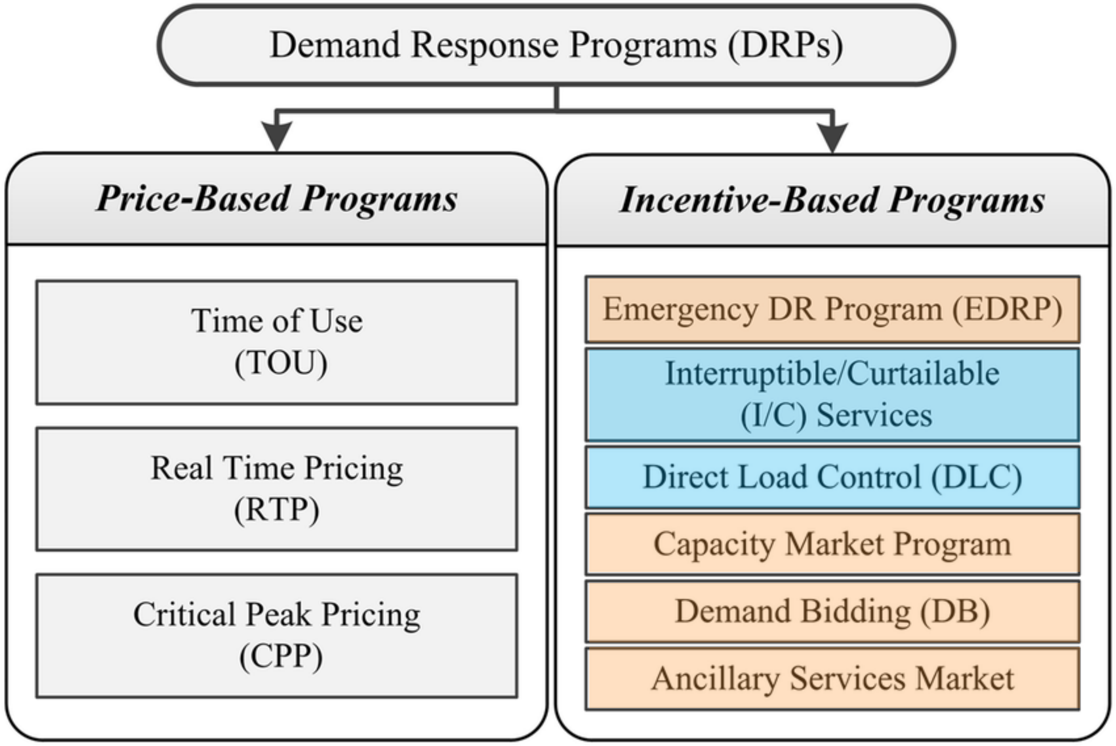
INTRO Demand Response Programs

Categories of demand response programs

- Complex metering / communication infrastructure
- May not respond to dynamic prices



+ Active participation of consumers

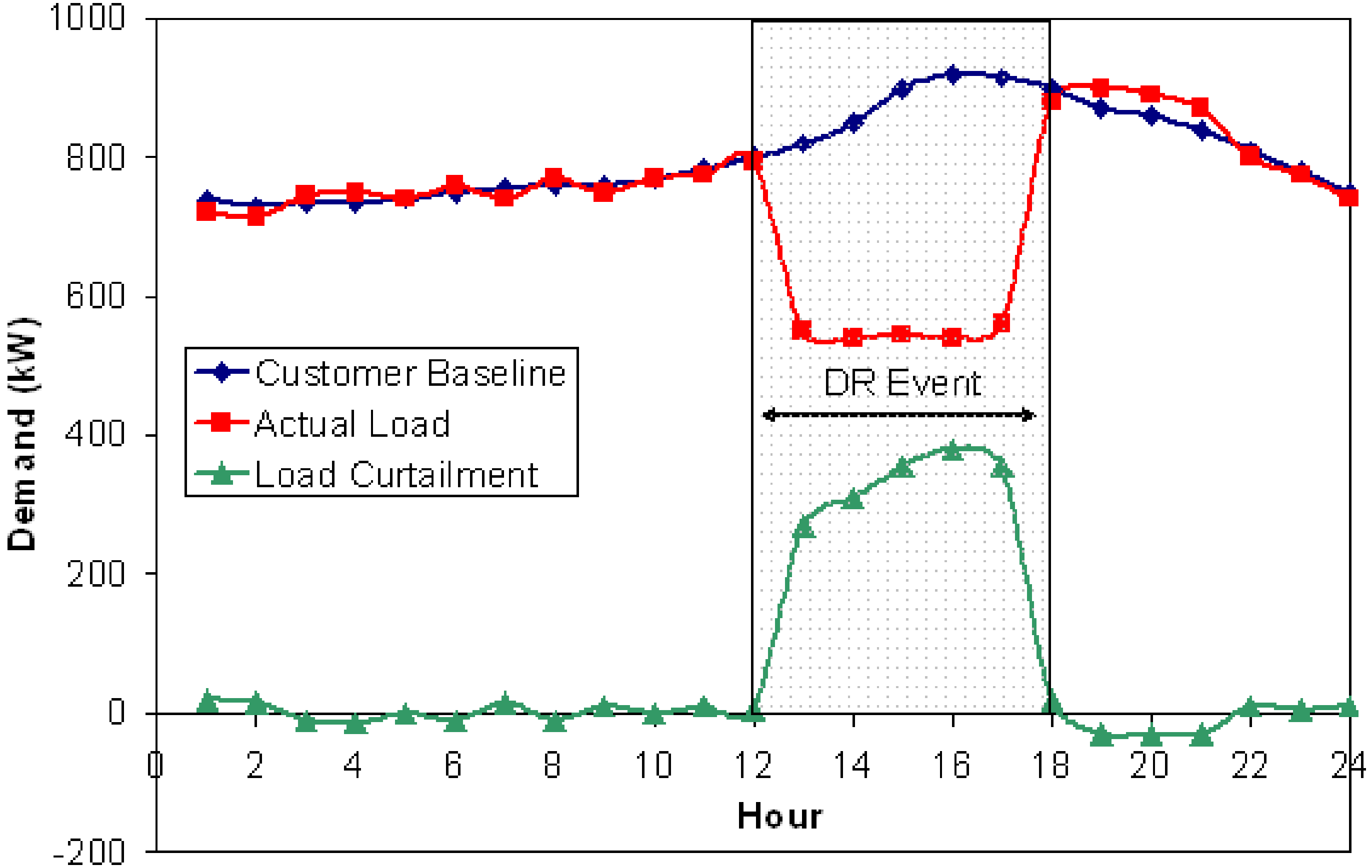
source: (2016 IEEE) Optimal Behavior of Electric Vehicle Parking Lots as Demand Response Aggregation Agents

INTRO Incentive-based Demand Response Programs

The process of reliability demand response program

INTRO Incentive-based Demand Response Programs

Components of incentive-based DR programs



1 Baseline

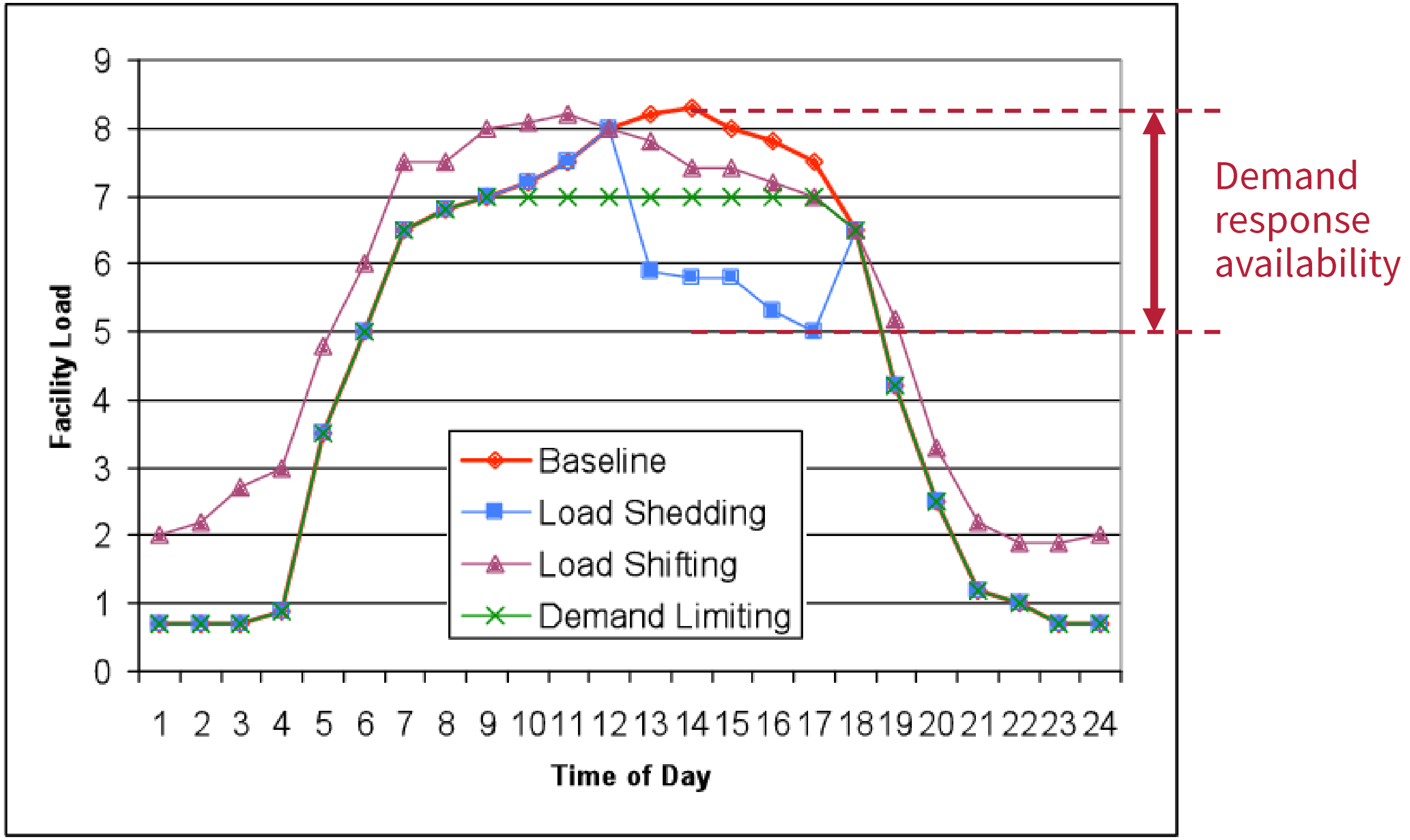
2 Payment scheme

3 Terms & Conditions

source: (2007 LBNL) Measurement, Verification, and Forecasting Protocols for Demand Response Resources

INTRO Incentive-based Demand Response Programs

Strategies for load reduction

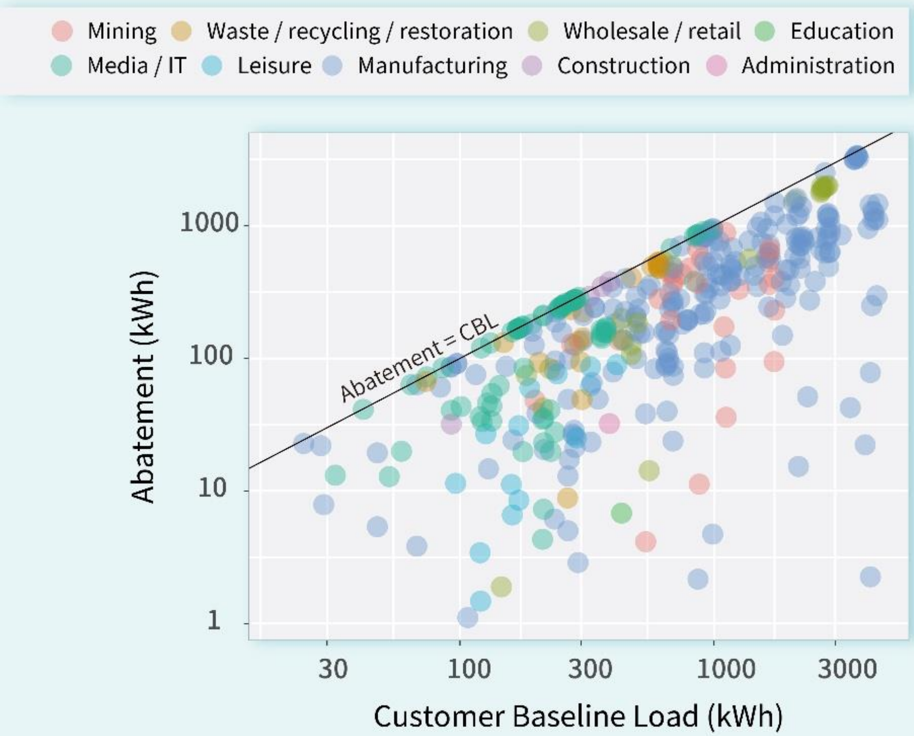


source: (2009 LBNL) Opportunities for Energy Efficiency and Open Automated Demand Response in Refrigerated Warehouses in California

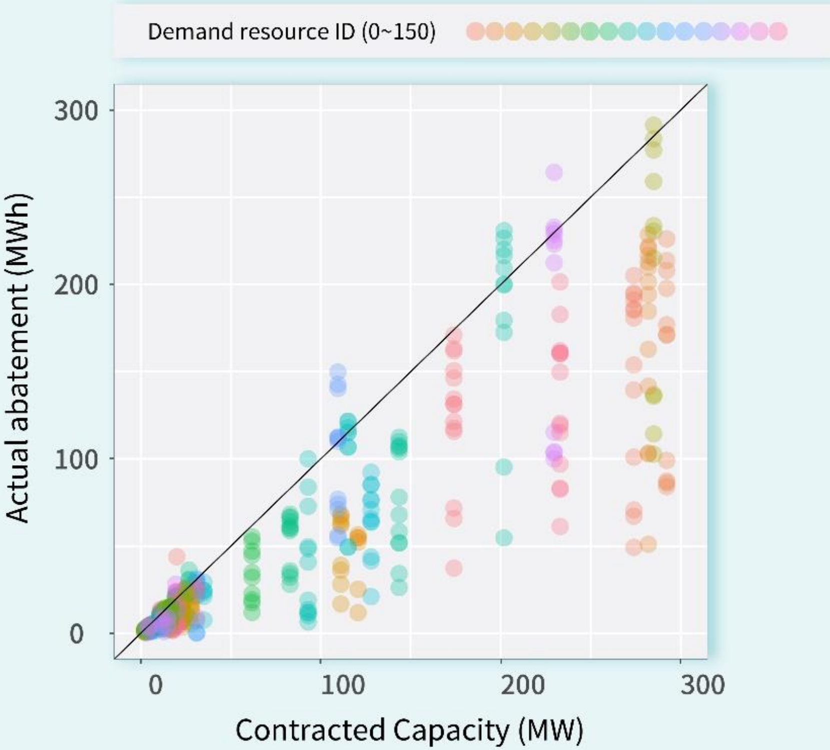
INTRO Research Motivation

Korea Power Exchange Reliability DR Program

(a) **Abatement and CBL** per industry category



(b) **Actual Abatement vs. Contracted Capacity**



INTRO Research Overview

Research Question

- Under customer heterogeneity in terms of DR availability, how can we increase service reliability and social welfare?
  - Private information about DR availability
  - Comparison between type-independent and type-dependent incentive contracts under such information asymmetry

Research Methodology

- Analytic model to gain insight about the research question
  - Utility maximization for agents (DR participants)
  - Profit maximization for the principal (utility firm)
  - Contract theory (hidden information) model

INTRO Related Literature

Optimal Contract for Incentive-based DR programs

Very recent studies solving various hidden action and hidden information problems

- Contract design to incentivize customers to not falsify the base load *(2016 Dobakhshari)*
- Novel demand response contract where a consumer self-reports his baseline and reduction to limit the baseline alteration *(2018 Vuelvas)*

✓ More focus on accurate measurement of base load

Heterogeneity in demand response availability in IBP

- Revelation mechanism for demand response incentives considering information asymmetry on knowledge of demand adjustments *(2013 Ramos)*
- Truthful and reliable mechanism that uses a reward-bidding approach to minimize response uncertainties, including variability in demand response units *(2017 Ma)*

✓ Mostly based on complex numerical analysis and simulating the proposed mechanism

MODEL Overview

Demand response program with 2 participants

CBL of each customer is measured and set as the reference point. Customers satisfying the individual rationality enter the program

Stage 1

The utility firm solves the maximization problem and offers the contract

Stage 2

Each type of participants choose the utility maximizing effort level and responds with corresponding demand reduction

MODEL Setup & Assumptions

Agents' utility maximization

- The same CBL level q_0 for the sake of simplicity
- Heterogeneous in DR availability $\theta_i \in \{\theta_L, \theta_H\}$, where different types respond with different load curtailment , $\Delta q_i = \theta_i \cdot e_i$ given the same effort level
- Exerts effort e_i, which is not observable to the principal, which costs $\Psi(e_i) = \frac{1}{2} e_i^2$
- Responds with demand reduction Δq_i, which is observable and verifiable, In response to incentive T_i

$$U_i = (q_0 - \Delta q_i) - p \cdot (q_0 - \Delta q_i) + T_i - \Psi(e_i)$$

MODEL Setup & Assumptions

Principal's profit maximization

- Reduces the total electricity demand Q_0 by demand response $\Delta q_L + \Delta q_H$
- $\mathrm{T_i}$ is paid to the agent according to the chosen incentive contract
- Payoffs decrease in profit from demand reduction with decrease in generation cost $C(Q) = \frac{k}{2}Q^2$
- Price of the electricity is permitted to be set as $(1+r)C(Q)$ with the rate of return r

$$\Pi = p \cdot (Q_0 - \Delta q_L - \Delta q_H) - \sum T_i - C(Q_0 - \Delta q_L - \Delta q_H)$$
$$= \frac{k}{2} r (Q_0 - \Delta q_L - \Delta q_H)^2 - \sum T_i$$

MODEL Type-independent Contract

Performance incentive not considering customer type: $T_i = I \cdot \Delta q_i$

Stage 2: Utility maximization of the agent

- The utility function of a type-i participant is:

$$U_i = q_0 - \Delta q_i - p \cdot (q_0 - \Delta q_i) + I \cdot \Delta q_i - \frac{\Delta q_i^2}{2\theta_i^2}$$

- First-order condition w.r.t Δq_i

$$-1 + \frac{k}{2}(r+1)(q_0 + Q_0) + I - (k(r+1) + \frac{1}{\theta_L^2})\Delta q_L - \frac{k}{2}(r+1)\Delta q_H = 0$$

$$-1 + \frac{k}{2}(r+1)(q_0 + Q_0) + I - (k(r+1) + \frac{1}{\theta_H^2})\Delta q_H - \frac{k}{2}(r+1)\Delta q_L = 0$$

- Δq_L^* and Δq_H^* as a function of I

$$\Delta q_L^* = \frac{-1 + X(q_0 + Q_0) + I}{(2X + \frac{1}{\theta_H^2})(\frac{X + \frac{1}{\theta_L^2}}{X + \frac{1}{\theta_H^2}})}$$

$$\Delta q_H^* = \frac{-1 + X(q_0 + Q_0) + I}{(2X + \frac{1}{\theta_L^2})(\frac{X + \frac{1}{\theta_H^2}}{X + \frac{1}{\theta_L^2}})}$$

MODEL Type-independent Contract

Performance incentive not considering customer type: $T_i = I \cdot \Delta q_i$

Stage 1: Profit maximization of the principal

- The profit function of the principal is:

$$\max_I p \cdot (Q_0 - \Delta q_L - \Delta q_H) - I \cdot (\Delta q_L + \Delta q_H) - C(Q_0 - \Delta q_L - \Delta q_H)$$
$$= \frac{k}{2} r (Q_0 - \Delta q_L - \Delta q_H)^2 - I(\Delta q_L + \Delta q_H)$$

- First-order condition w.r.t I

$$F.O.C_I : -krQ_0D - krD^2 + KrD^2X(q_0 + Q_0) + D - DX(q_0 + Q_0) + (KrD^2 - 2D)I^* = 0$$

- Value of $\Delta q_L^*, \Delta q_H^*, I$

$$X := \frac{k}{2}(r+1)$$
$$D := \frac{1}{(2X + \frac{1}{\theta_H^2})(\frac{X + \frac{1}{\theta_L^2}}{X + \frac{1}{\theta_H^2}})} + \frac{1}{(2X + \frac{1}{\theta_L^2})(\frac{X + \frac{1}{\theta_H^2}}{X + \frac{1}{\theta_L^2}})}$$

$$I^* = 1 - X(Q_0 + q_0) + \frac{1 - X(q_0 + Q_0) - KrQ_0}{KrD - 2}$$

$$\Delta q_L^* = \frac{1 - X(q_0 + Q_0) - KrQ_0}{(KrD - 2)(2X + \frac{1}{\theta_H^2})(\frac{X + \frac{1}{\theta_L^2}}{X + \frac{1}{\theta_H^2}})}$$

$$\Delta q_H^* = \frac{1 - X(q_0 + Q_0) - KrQ_0}{(KrD - 2)(2X + \frac{1}{\theta_L^2})(\frac{X + \frac{1}{\theta_H^2}}{X + \frac{1}{\theta_L^2}})}$$

MODEL Type-dependent Contract

Performance incentive considering customer type: $T_i = I_i \cdot \Delta q_i$

(1) Full information scenario

- Individual rationality constraint (binding)

$$(IR_L^{**}) : q_0 - \Delta q_L^{**} - \frac{k}{2}(Q_0 - \Delta q_L^{**} - \Delta q_H^{**})(r+1)(q_0 - \Delta q_L^{**}) + I_L \Delta q_L^{**} - \frac{1}{2}\frac{\Delta q_L^{**2}}{\theta_L^2}$$
$$= q_0 - \frac{k}{2} Q_0 (r+1) q_0$$

$$(IR_H^{**}) : q_0 - \Delta q_H^{**} - \frac{k}{2}(Q_0 - \Delta q_L^{**} - \Delta q_H^{**})(r+1)(q_0 - \Delta q_H^{**}) + I_H \Delta q_H^{**} - \frac{1}{2}\frac{\Delta q_H^{**2}}{\theta_H^2}$$
$$= q_0 - \frac{k}{2} Q_0 (r+1) q_0$$

- I_L and I_H as a function of Δq_L^{**} and Δq_H^{**}

$$I_L = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_L^2})\Delta q_L^{**} + X \Delta q_H^{**} - X q_0 \frac{\Delta q_H^{**}}{\Delta q_L^{**}}$$

$$I_H = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_H^2})\Delta q_H^{**} + X \Delta q_L^{**} - X q_0 \frac{\Delta q_L^{**}}{\Delta q_H^{**}}$$

MODEL Type-dependent Contract

Performance incentive considering customer type: $T_i = I_i \cdot \Delta q_i$

(1) Full information scenario

- Profit maximization of the principal: First-order condition w.r.t Δq_L^{**} and Δq_H^{**}

$$\Delta q_L^{**} = \frac{k(r+1)q_0 - \frac{k}{2}(r-1)Q_0 - 1}{k(1+\frac{\theta_H^2}{\theta_L^2}) + \frac{1}{\theta_L^2}}$$

$$\Delta q_H^{**} = \frac{k(r+1)q_0 - \frac{k}{2}(r-1)Q_0 - 1}{k(1+\frac{\theta_L^2}{\theta_H^2}) + \frac{1}{\theta_H^2}}$$

MODEL Type-dependent Contract

Performance incentive considering customer type: $T_i = I_i \cdot \Delta q_i$

(2) Asymmetric information scenario

- Individual rationality & incentive compatibility constraint (binding IR_L and IC_H)

$$(IR_L^{***}) : q_0 - \Delta q_L^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_L^{***}) + I_L \Delta q_L^{**} - \frac{1}{2}\frac{\Delta q_L^{***2}}{\theta_L^2}$$
$$= q_0 - \frac{k}{2} Q_0 (r+1) q_0$$

$$(IR_H) : q_0 - \Delta q_H^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_H^{***}) + I_H \Delta q_H^{***} - \frac{1}{2}\frac{\Delta q_H^{***2}}{\theta_H^2}$$
$$\geq q_0 - \frac{k}{2} Q_0 (r+1) q_0$$

$$(IC_L) : q_0 - \Delta q_L^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_L^{***}) + I_L \Delta q_L^{**} - \frac{1}{2}\frac{\Delta q_L}{\theta_L^2}$$
$$\geq q_0 - \Delta q_H^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_H^{**}) + I_H \Delta q_H^{***} - \frac{1}{2}\frac{\Delta q_H^{***2}}{\theta_L^2}$$

$$(IC_H^{***}) : q_0 - \Delta q_H^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_H^{***}) + I_H \Delta q_H^{***} - \frac{1}{2}\frac{\Delta q_H^{***2}}{\theta_H^2}$$
$$= q_0 - \Delta q_L^{***} - \frac{k}{2}(Q_0 - \Delta q_L^{***} - \Delta q_H^{***})(r+1)(q_0 - \Delta q_L^{***}) + I_L \Delta q_L^{***} - \frac{1}{2}\frac{\Delta q_L^{***2}}{\theta_H^2}$$

MODEL Type-dependent Contract

Performance incentive considering customer type: $T_i = I_i \cdot \Delta q_i$

(2) Asymmetric information scenario

- I_L and I_H as a function of Δq_L^{***} and Δq_H^{***}

$$I_L = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_L^2})\Delta q_L^{***} + X\Delta q_H^{***} - X q_0 \frac{\Delta q_H^{**}}{\Delta q_L^{***}}$$

$$I_H = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_H^2})\Delta q_H^{***} + X\Delta q_L^{***} - X q_0 \frac{\Delta q_L^{***}}{\Delta q_H^{***}} + \frac{1}{2}(\frac{1}{\theta_L^2} - \frac{1}{\theta_H^2})\frac{\Delta q_L^{***2}}{\Delta q_H^{***}}$$

- Profit maximization of the principal: First-order condition w.r.t Δq_L^{***} and Δq_H^{***}

$$\Delta q_L^{***} = \frac{k(r+1)q_0 - \frac{k}{2}(r-1)Q_0 - 1}{2k\frac{\theta_H^2}{\theta_L^2} + \frac{2}{\theta_L^2} - \frac{1}{\theta_H^2}}$$

$$\Delta q_H^{***} = \frac{k(r+1)q_0 - \frac{k}{2}(r-1)Q_0 - 1}{k + \frac{1}{\theta_H^2} + \frac{k\theta_L^2}{2\theta_H^2 - \theta_L^2}}$$

RESULT Comparison between Different Scenarios

Optimal incentive rate

Type-independent

$$1 - X(Q_0 + q_0) + \frac{1 - X(q_0 + Q_0) - KrQ_0}{KrD - 2}$$

Type-dependent

(1) Full information

$$I_L = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_L^2})\Delta q_L^{**} + X\Delta q_H^{**} - Xq_0\frac{\Delta q_H^{**}}{\Delta q_L^{**}}$$

$$I_H = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_H^2})\Delta q_H^{**} + X\Delta q_L^{**} - Xq_0\frac{\Delta q_L^{**}}{\Delta q_H^{**}}$$

(2) Asymmetric information

$$I_L = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_L^2})\Delta q_L^{***} + X\Delta q_H^{***} - Xq_0\frac{\Delta q_H^{**}}{\Delta q_L^{***}}$$

$$I_H = 1 - X(q_0 + Q_0) + (X + \frac{1}{2\theta_H^2})\Delta q_H^{***} + X\Delta q_L^{***} - Xq_0\frac{\Delta q_L^{***}}{\Delta q_H^{***}} + \frac{1}{2}(\frac{1}{\theta_L^2} - \frac{1}{\theta_H^2})\frac{\Delta q_L^{***2}}{\Delta q_H^{***}}$$

Demand response performance of each type

Type-independent

$$\Delta q_L^* = \frac{1 - X(q_0 + Q_0) - KrQ_0}{(KrD - 2)(2X + \frac{1}{\theta_H^2})(\frac{X + \frac{1}{\theta_L^2}}{X + \frac{1}{\theta_H^2}})}$$

$$\Delta q_H^* = \frac{1 - X(q_0 + Q_0) - KrQ_0}{(KrD - 2)(2X + \frac{1}{\theta_L^2})(\frac{X + \frac{1}{\theta_H^2}}{X + \frac{1}{\theta_L^2}})}$$

Type-dependent

(1) Full information

$$\Delta q_L^{**} = \frac{k(r + 1)q_0 - \frac{k}{2}(r - 1)Q_0 - 1}{k(1 + \frac{\theta_H^2}{\theta_L^2}) + \frac{1}{\theta_L^2}}$$

$$\Delta q_H^{**} = \frac{k(r + 1)q_0 - \frac{k}{2}(r - 1)Q_0 - 1}{k(1 + \frac{\theta_L^2}{\theta_H^2}) + \frac{1}{\theta_H^2}}$$

v ∧

(2) Asymmetric information

$$\Delta q_L^{***} = \frac{k(r + 1)q_0 - \frac{k}{2}(r - 1)Q_0 - 1}{2k\frac{\theta_H^2}{\theta_L^2} + \frac{2}{\theta_L^2} - \frac{1}{\theta_H^2}}$$

$$\Delta q_H^{***} = \frac{k(r + 1)q_0 - \frac{k}{2}(r - 1)Q_0 - 1}{k + \frac{1}{\theta_H^2} + \frac{k\theta_L^2}{2\theta_H^2 - \theta_L^2}}$$

Summary Findings & Contribution

- Information rent created from asymmetry of information in agents' DR availability
- Distortion in demand response in both low and high type participants
- Novel approach in using abatement quantity as a signal to differentiate customer types with the same baseline load and different DR availability
- Giving insights on how incentive-based DR contracts could be enhanced in terms of contract reliability and ultimately service reliability

Conclusion Limitations & Future Works

- Complex results hard to interpret
  - ➢ Further analysis regarding total profit and social welfare
- Stylized model with limited insights
  - ➢ Verification through empirical data
  - ➢ Counterfactual analysis

The End.

Thank you for listening!

This is the end of my presentation.
Feedbacks and questions are more than welcome.

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