Demand Response with Incomplete Information

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Overview

We study demand response procurement in the electricity sector. Currently, many consumers have the option to buy electricity at a fixed retail rate, which leads to inefficiently high demand when the marginal cost of producing electricity exceeds the retail rate. In response, a load-serving entity (LSE) or demand response (DR) aggregator can develop a demand response program to reduce consumption. In many jurisdictions, the LSE can only incentivize customers; it cannot penalize them or charge them more than the regulated retail rate. The LSE also cannot observe customers' utility functions, which are private information. We seek to determine the optimal demand response incentive when consumers have private information and the principal can not penalize consumers. We present conditions for the optimal (piecewise) linear contract; consumers get paid per unit of reduction below an established baseline. Contrary to common practice, it is rarely optimal to make the baseline the expected value of the counter-factual consumption at the retail rate, even in the absence of strategic behavior by consumers. We extend numerical examples from (Chao, 2010) to emphasize the cost of incomplete information.

Methods

We develop a model of demand response where the customer utility function and their counterfactual energy consumption are private information. We use tools from microeconomics, contract theory, and optimization to derive results, with the goal of understanding how aggregators and load-serving entities should optimally contract for demand response in the presence of incomplete and private information.

Consider a single consumer with type θ, which defines a concave, increasing utility function for consuming electricity U_θ. The consumer has an existing option to purchase electricity (per kWh) from a utility or LSE at a flat retail rate *R*. The cost of electricity is *c*, so the profit from the sale of energy, as a function of customer consumption q is $(R - c)q$. We can think of the LSE as a private firm with their own objectives, or as a decision maker acting on behalf of the group of customers it represents. Throughout, we will frequently refer to the LSE as the principal, and the consumer as the agent. If the principal profits from the sale of electricity, or maximizes the social welfare of agents, then when $c > R$ the principal might prefer that consumers reduce their consumption.

The principal has the option to offer a demand response incentive $f(q)$ in order to encourage consumers to reduce their demand, but for regulatory reasons and due to the existing contract with the consumer, $f(q) \geq 0$. The objective function for the consumer/agent is $U_\theta(q) - q\,R$ in the absence of a demand response program and $U_\theta(q) - q\,R + f(q)$ in the presence of the demand response program. The agent chooses $q_\theta = \arg\max U_\theta(q) - qR + f(q)$.

The principal chooses $f(q)$ to optimize their own objective function; they don't know the consumer's type θ, which is private information, but they have a probability distribution $\mathbb{P}(\theta)$ over the possible types. The principal's objective could be, for instance, to maximize social welfare or to minimize their total costs for energy procurement; we focus, first, on the former.

Demand response programs impute a baseline β, which is typically intended to measure how much electricity a consumer would have used in the absence of the program, i.e. $\beta = \mathbb{E}[q_\theta]$ when $f(q) = 0$. We take a slightly different approach and define focus on the threshold γ that describes the point below which the customer beings earning money in the demand response program: $\gamma = \arg\sup \{q \mid f(q) = 0\}$. This definition is helpful because the functional importance of the threshold is that it describes the point at which the demand response payment hits 0. It captures the core use case of threshold, which is that it describes the intercept for the demand response incentive function. In many existing programs, the term baseline is used interchangeably with the demand response threshold, and the threshold γ is set to β.

Results

We derive results that explain consumption by the agents (consumers) in the presence or absence of demand response programs. Then, we incorporate this result endogenously to determine the optimal demand response offering strategy by the principal (LSE, utility, or aggregator). We determine conditions for an optimal piecewise linear demand response incentive, where, as in most existing programs, the LSE pays consumers a fixed rate per unit of demand reduction below a defined threshold.

We establish that this threshold should not, in general, be equal to the expected value of the consumption in the absence of the demand response program. That is, in general $\boldsymbol{\gamma} \neq \boldsymbol{\beta}$. We explain the result and offer extensions.

Furthermore, we extend the results to model welfare in existing demand response programs with incomplete information. We extend Hung-Po Chao's (2010) model to incorporate incomplete information and find that incomplete information substantially degrages the value of a demand response program.

Conclusions

The existing paradigm for demand response programs, in the presence of incomplete information, typically sets an incentive threshold at the consumer baseline. These programs estimate the consumer baseline as the extent of energy consumed in the absence of the demand response program, and they pay consumers for reductions below that baseline. We argue that this is not socially optimal, even without considering the potential for moral hazard. We present alternatives to improve social welfare, using tools from microeconomics and contract theory. We also suggest additional methods for a more general class of demand response incentive designs, and we discuss methods for reducing moral hazard. In an example, we quantify the cost of incomplete information based on demand response programs under current practice.

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