Equitable Time-Varying Pricing Tariff Design: A Joint Learning and Optimization Approach

COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

Liudong Chen [1] Bolun Xu [1]

[1]Earth and Environmental Engineering, Columbia University, New York, NY 10027

Abstract

Time-varying pricing tariffs incentivize consumers to shift their electricity demand and reduce costs, but may increase the energy burden for consumers with limited response capability. The utility must thus **balance affordability and response incentives** when designing these tariffs by considering consumers' response expectations. This paper proposes a joint learning-based identification and optimization method to design equitable time-varying tariffs. Our proposed method encodes historical prices and demand response data into a recurrent neural network (RNN) to capture high-dimensional and non-linear consumer price response behaviors. We then embed the RNN into the tariff design optimization, formulating a **non-linear optimization problem with a quadratic objective**. We propose a gradient-based solution method that achieves fast and scalable computation. Simulation using real-world consumer data shows that our equitable tariffs **protect low-income consumers from price surges while effectively motivating consumers to reduce peak demand**. The method also ensures **revenue recovery for the utility company** and achieves robust performance against demand response uncertainties and prediction errors.

Challenges

- Price should reflect wholesale market prices, distribution grid security constraints, and consumers' willingness to respond.
- Address energy equity as time-varying prices increases the electricity cost for low-income consumers who can't afford high price and lack the means to reduce demand during the peak price period

Proposed Method

We formulate a joint learning and optimization approach to design **equitable and effective pricing tariff** considering time-coupled price-response behavior and social demographics of consumers:

$$\min_{p_i} f = \sum_{i\in\mathcal{I}} \left(\left[\frac{D_i^T p_i}{I_i} - \overline{E}\right]^+\right)^2 + \alpha\|p_i - \lambda\|_2^2 \quad (1a)$$

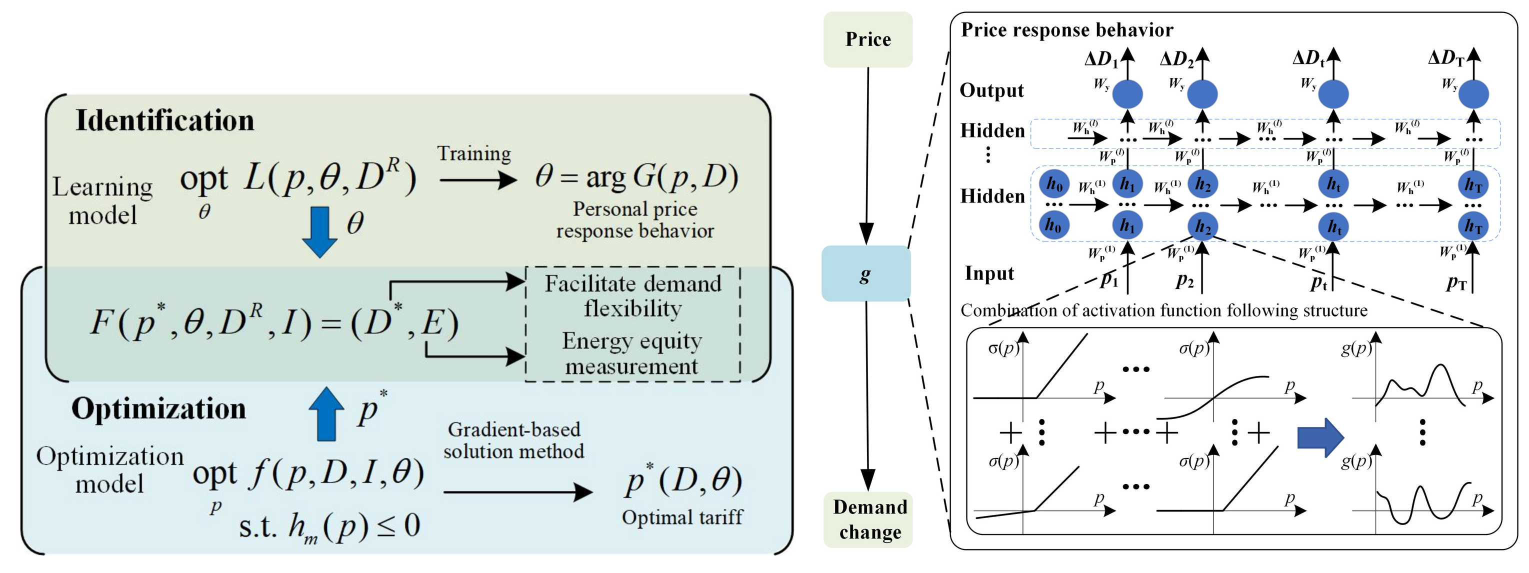
s.t.

$$D_i = G_i(p_i|\theta_i) \quad (1b)$$

$$\sum_{i\in\mathcal{I}} D_i^T p_i \geq C + D_{0,i}^T\lambda \quad (1c)$$

$$p_i = p_j,\ \forall i,j \in \mathcal{I}_n, \forall n \in \mathcal{N} \quad (1d)$$

We cluster consumers according to their energy burden and embed a recurrent neural network (RNN) structure $G_i(p_i|\theta_i)$ to reflect their price response behavior. We express the whole approach in Fig. 1.



(a) Joint learning and optimization framework (b) Modeling consumers' price responses behaviors

Figure 1. Equitable and effective tariff design approach.

We train and update the RNN model parameters using past price data and observed consumer demand D_i^R in response to the instructed prices:

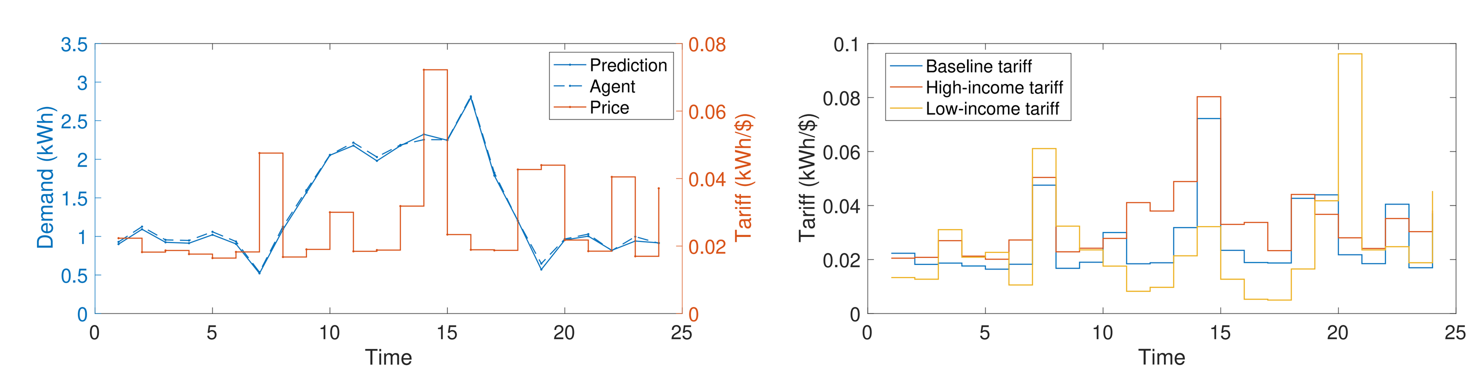
$$\min_{\theta} L = \|G_i(p_i|\theta) - D_i^R\|_2^2 \quad (2)$$

The model is subject to operators' revenue recovery and demand reduction constraints.

Equitable and Effective Tariff Results

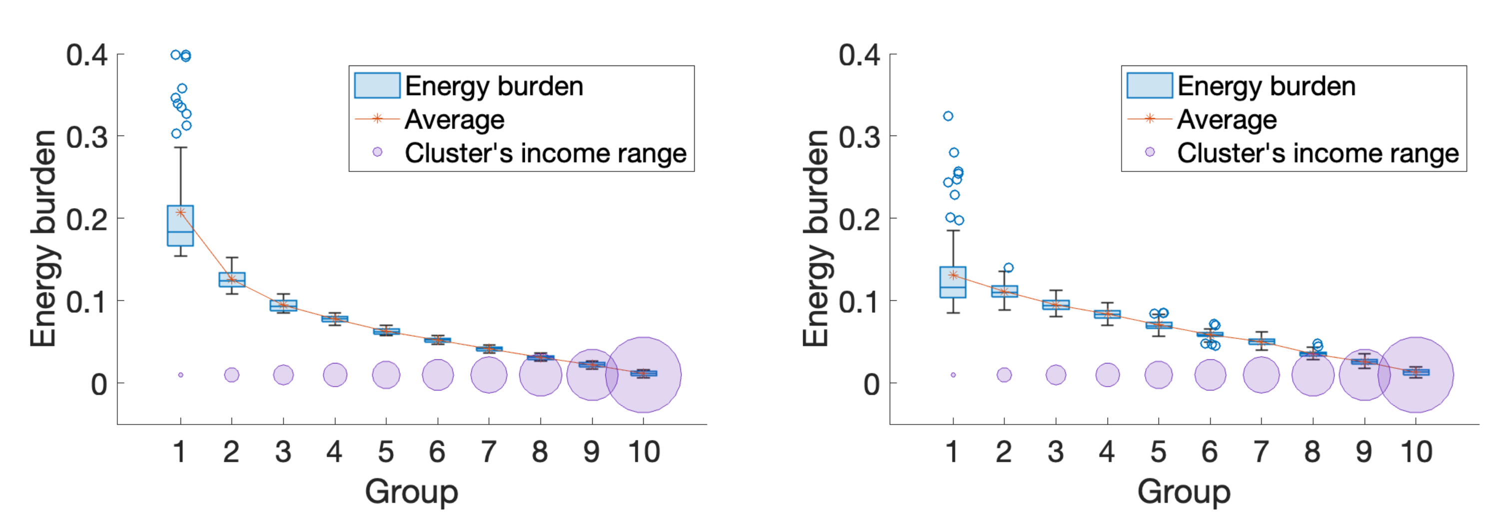
We use the raw data of Austin, Texas, from ERCOT, which includes day-ahead hourly price and load consumption data of 1000 consumers in 2018. We calculate their demand change during price response processes using the agent model.

We then show price response identification results, time-varying equitable tariffs, and energy burden results.



(a) Learning results (b) Tariffs in low-income group and high-income group

Figure 2. Consumers' price response behavior identification.

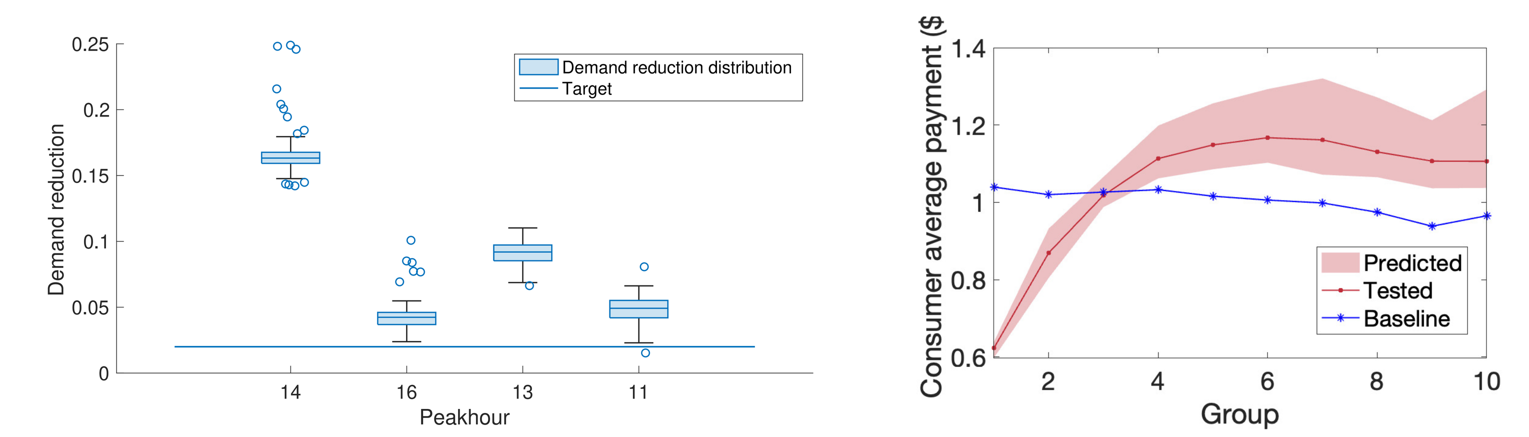


(a) Baseline tariff (b) Proposed tariff

Figure 3. Consumers' energy burden under different tariffs.

- We modified the baseline tariff, which is the existing wholesale market tariff under the DR program.
- Fig. 3 demonstrates that our method accurately captures consumer price response behavior. **Our tariffs are reduced for low-income consumers and increased for high-income consumers**, particularly during peak time slots.
- Both figures illustrate how **our method addresses energy inequity by implementing tiered tariffs for high- and low-income consumers**. This helps **redistribute the energy burden among consumers and provides protection to low-income consumers during DR events**.

To validate the proposed tariffs' DR effect and revenue recovery performance, we compare the agent model results with the identification results.



(a) Demand reduction effect (b) Consumers' payment

Figure 4. Model validation with consumers' individual agent model.

- The peak demand reduction targets can be achieved in most cases with minor variations.
- The average consumer payment further attests to the reliability of our method. It shows **minor variation among consumers at different income levels**.

California started using high electricity prices (fixed parts) for high-income consumers. We are now entering a new era. Also, as we modify the DR tariff, although high-income consumers' payment is slightly higher than that of low-income consumers, all consumers can still benefit by participating in the DR program and receiving the time-varying tariffs.

The data and code used in this study are available from the authors upon reasonable request.

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