Approximately Stable Pricing for Coordinated Purchasing of Electricity

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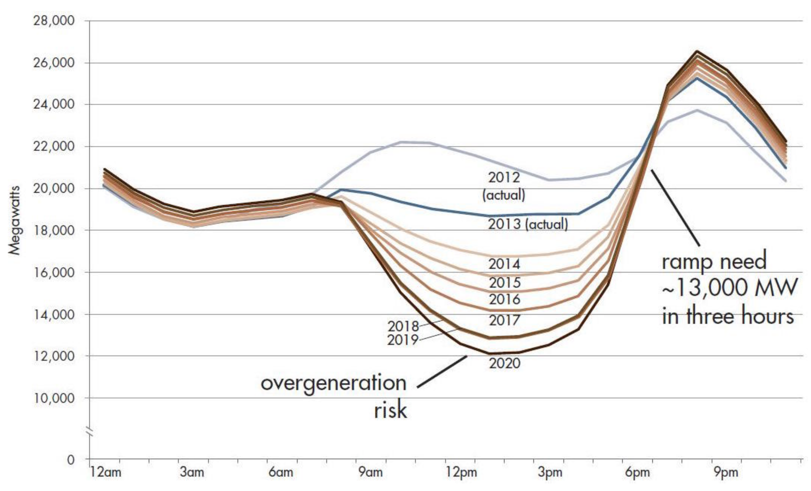
Contributions

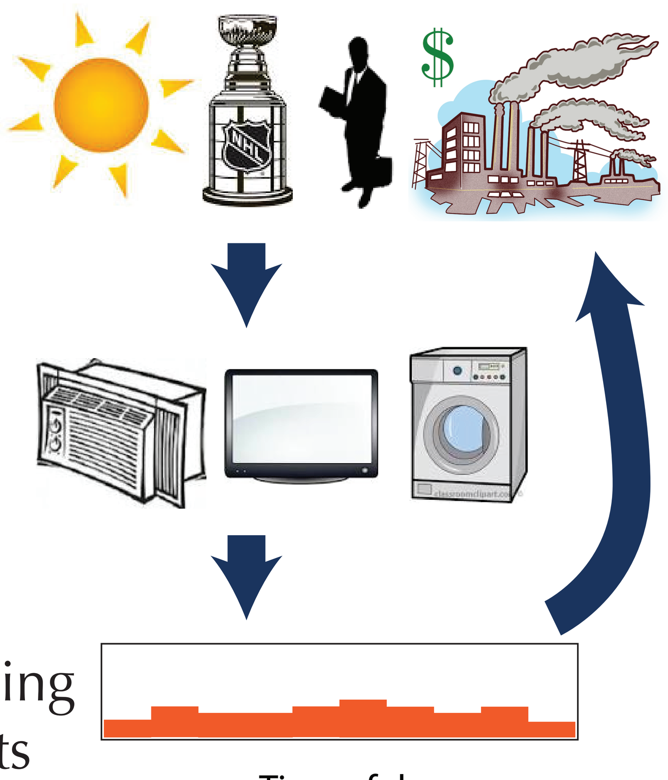
- Develop model of electricity markets that accounts for many of the complexities in demand and production
- Complexities prevent use of standard cost-sharing techniques
- We develop cost-sharing schemes that address stability, envy-freeness, transparency, budget balance, and scalability

Motivation

- Make demand more responsive to grid conditions
- Make it cheaper to integrate renewable sources, which generate a varying amount of power, into the grid

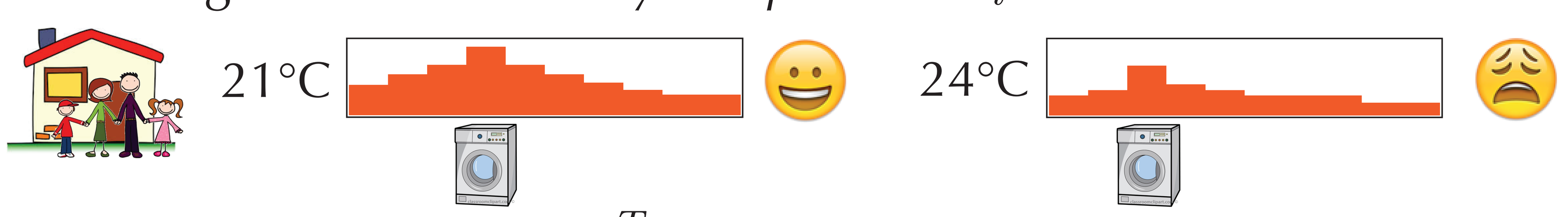


- Consumers willing to change their behavior if they are sufficiently compensated and if it is not too annoying
- Problem: consumers respond slowly to incentives
- Approach: each consumer is represented by an autonomous agent, who knows their preferences
- We focus on the problem of coordinating agents and determining "fair" payments that incentivize consumers to coordinate

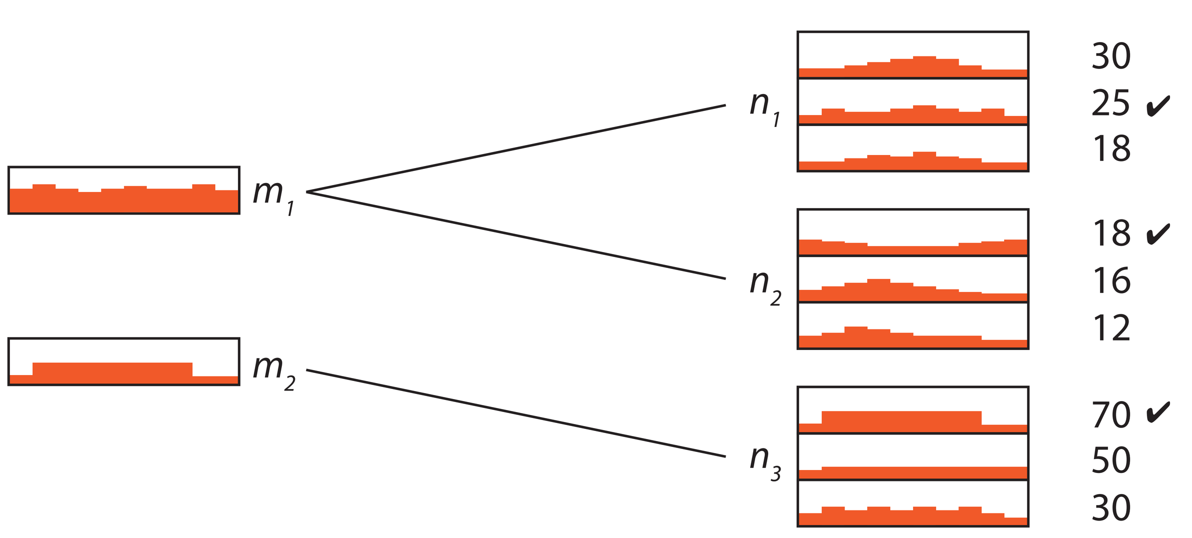


Model

- Each agent i has *electricity use profiles* Π_i



- Each profile $\boldsymbol{\pi} \in \Pi_i \subset \mathbb{R}^T$ represents an acceptable consumption pattern (electricity use per period in kwh)
- Each *profile* has a value $V_i(\boldsymbol{\pi})$ in dollars
- Matching μ maps consumer i to a producer $\mu(i)$ and a profile $\mu^p(i)$
- Each producer j has a *price function* $P_j : \mathbb{R}^T \rightarrow \mathbb{R}$ representing what they would charge for serving a particular demand profile
  - Limited *ramp rate*
  - *Shutdown costs*: if demand < *minimum economic generation level (MEGL)*, an additional fee is charged
  - *Base layer*: inexpensive, slow to adjust
  - *Tracking layer:* expensive, quickly adjustable
- Social welfare: sum of profile values minus sum of producer prices



- Social welfare optimization can be formulated as an integer program where most integer variables may be relaxed
  - $O(MT)$ binary variables (T time periods, M producers)
  - Can solve relatively large instances: 5000 agents, 2 producers, 4 profiles, 24 time periods—in 15 min.

Approach to Cost Sharing

- View as a cooperative game
- Coalitions consist of a producer and consumer agents, value is social welfare
- Negative results: core and Nash-stable allocations may not exist

Desiderata

- *Stability* and *budget balance*
- *Envy-free*: no agent would prefer the matching of an identical agent
- *Transparent*: it should be clear why an agent is paying what they pay
- Computationally scalable: tractable for large numbers of agents

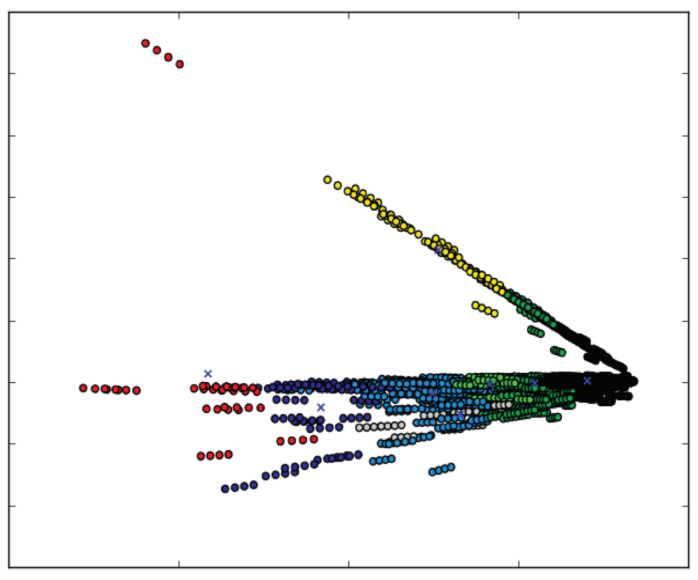
Shapley-Like Payments

- We can apply Shapley values. The Shapley value of consumer n_0 matched to producer m_0 under μ is:

$$s(n_0) = \alpha \sum_{S \in \mu^{-1}(m_0) \setminus \{n_0\}} P_{m_0}(\mathrm{dem}_\mu(S \cup \{n_0\})) - P_{m_0}(\mathrm{dem}_\mu(S))$$

- α is a normalizing constant, $dem_\mu(x)$ is the demand of the agents in set x under matching μ
- Intuition: Shapley payment for n_0 is the average marginal cost over all orders that n_0 could be assigned to producer m_0
- We allow payments to be adjusted ±10% to increase stability

Similarity-Based Envy-Free Payments

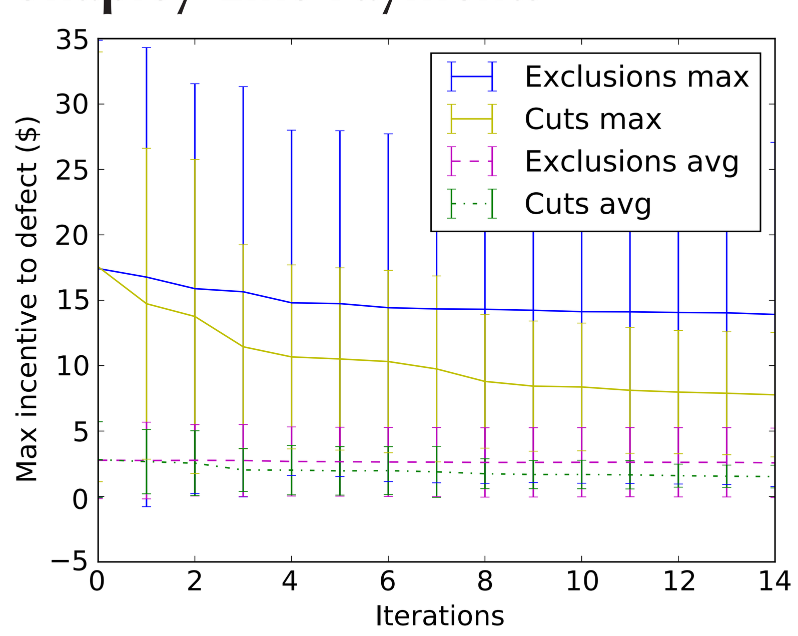


- Envy-freeness is very weak in this context because usually no two agents will want to use the same profile
- Similarity-based envy-freeness (SBEF) generalizes envy-freeness: demand profiles that are "close" should have a similar price
- Partition demand profiles, fix unit price in each partition, and optimize prices for stability
- Intuition: SBEF payments are fair because consumers with profiles in different clusters pressure payments to be similar across partitions

Experiments

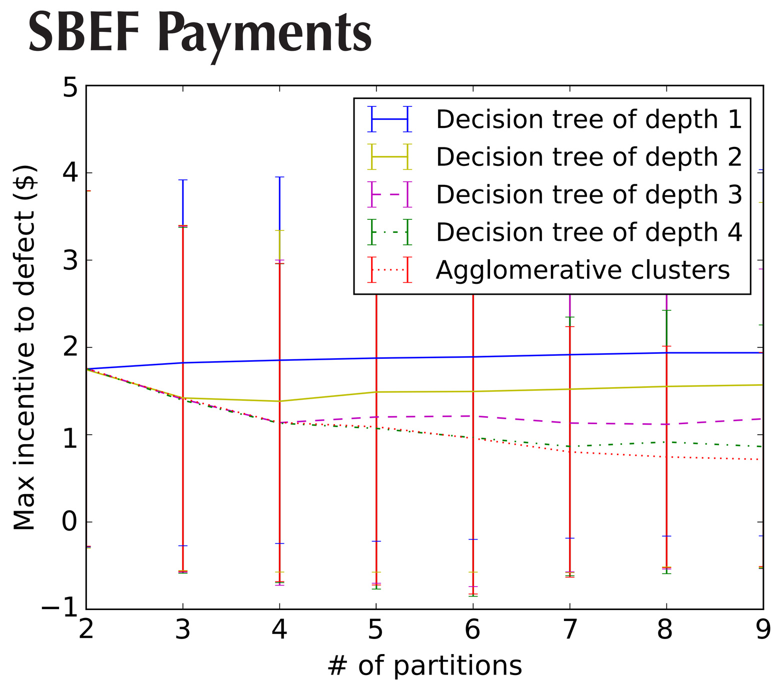
- 50 consumers, 2 producers, 4 profiles per consumer, 50 trials
- Model of residential energy use in San Antonio, Texas, July

Shapley-Like Payments



- Do a local search to improve stability while sacrificing a small amount of social welfare (< 2%)
- Payments have max defection incentive of $7.5 on avg.
- Computationally expensive
- Well-understood

SBEF Payments



- Very stable: max defection incentive is less than $2
- Computationally efficient: we can solve instances with 2500 in 30 minutes
- Stability ↑, envy-freeness ↓ as number of partitions ↑

Future Work

- Elicitation of demand profiles
  - Make use of historical data
- Use envy-freeness partitions to compress optimization
- SBEF partitioning scheme that supports goals of mechanism
  - Avoid bad partitions
- SBEF in other contexts