Approximately Stable Pricing for Coordinated Purchasing of Electricity

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Shortcomings of the Traditional Grid

- Lots of reserve capacity
- Renewable integration
Consumer Behavior

- Consumers willing to shift or reduce
  - If they are sufficiently compensated
  - If it’s not too annoying to do so
- Behaviors must be coordinated

[Bar charts showing demand in kWh for 12 pm and 1 pm with a shift towards lower demand in the evening hours.]
Model of Consumer Decisions

The World

Consumer Actions

Demand Profile

Demand in kwh

Time of day
Home Energy Management Agents

The World

Consumer Actions

Demand Profile

Demand in kwh

Time of day
Coordinating Consumer Behavior

• Two decisions to make
  • What actions should agents take?
  • How should agents be compensated?
• Agents are self-interested
Outline

• Introduction ✓
• Setting and Optimization
• Cost Sharing Schemes
• Experiments
Consumer Model

• Each consumer \(i\) has electricity use profiles \(\Pi_i\)
  
  • Each profile \(\boldsymbol{\pi} \in \Pi_i \subset \mathbb{R}^T\) \((T\) time periods\)
  
  • Each profile has a value \(V_i(\boldsymbol{\pi})\) in dollars

21 °C

24 °C
Producer Model

• Each producer $j$ has price function $P_j : \mathbb{R}^T \rightarrow \mathbb{R}$

• Limited ramp rate

• Base layer: inexpensive, slow to adjust
  • Has shutdown costs

• Tracking layer: expensive, quick to adjust
Matching

• Matching $\mu$ maps consumers to producers and profiles

• Social welfare of $\mu$: sum of profile values minus sum of producer prices

<table>
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<th>producers</th>
<th>matching</th>
<th>consumers</th>
<th>value ($)</th>
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</table>
Optimal Coordination

• Find social welfare-maximizing matching
• Formulate as a mixed integer program
  • Relax matching variables
  • Require binary variables for each producer
  • Scalable: 5000 agents, 2 producers, 4 profiles, 24 time periods in 15 min.
    • ~55k continuous variables, 144 binary
Outline

• Introduction ✓
• Setting and Optimization ✓
• **Cost Sharing Schemes**
• Experiments
Cost Sharing

• View as a cooperative game
• Each coalition consists of one producer, multiple consumers
• Characteristic function $f : 2^{\text{NUM}} \rightarrow \mathbb{R}$
Cost Sharing Desiderata

• **Stable**: no defections
• **Budget-balanced**: all payments collected
• **Envy-free**: no agent prefers allocation of another agent
• **Transparent**: easy to reason about
• Computationally scalable
Core and Nash-Stable Payments

• Core payments
  • Prevent all defections
  • May not exist

• Nash-stable payments
  • Prevent defections of any single agent
  • May not exist
Shapley-Like Payments

• Want to apply Shapley values
• Shapley value for consumer $n_0$ who is matched to producer $m_0$:
  • Consider all orders agents could join $m_0$
  • In each, look at the cost imposed by adding $n_0$
  • $n_0$’s Shapley value = avg. marginal cost over all join orders
• We adjust the payments for stability
• Computationally expensive
  • Use sampling
Similarity-Based Envy-Freeness

- Envy-freeness is a weak concept in this setting
  - Rarely will two agents have the same profile
- Generalize envy-freeness

10¢/kwh

20¢/kwh
Similarity-Based Envy-Freeness Payments

• *Similarity-based envy-free payments*
  • Partition demand profiles
  • Fix the unit price in each partition
  • Optimize prices for stability
• More partitions = more flexible payments, more stability, less envy-freeness
• Intuition: prices fair because some agents have profiles in different partitions
  • Creates pressure for adjacent partitions to have competitive prices via the stability objective
• Scalable: 2500 consumers, 2 producers, 4 profiles, 24 time periods in 30 min.
Outline

• Introduction ✓
• Setting and Optimization ✓
• Cost Sharing Schemes ✓
• Experiments
Experimental Setting

• 50 consumers, 2 producers, 4 profiles per consumer, 50 trials
  • Computational reqs. of Shapley-like payments
• Heating and cooling model based on US residential energy use data
• Weather: hot summer day
Shapley-Like Payments

- Can reduce maximum incentive to defect to around $7.5 with tuned Shapley-like Payments
  - Sacrifice a little bit of social welfare, < 2%
Similarity-Based Envy-Free Payments

• Very low max incentive to defect, < $1.75, even when using a small number of partitions
• Can increase the number of partitions to further increase stability
Conclusion

• Market model for matching electricity producers and consumers
  • Consumers may have multiple demand profiles

• Analysis of two cost sharing schemes

• Work towards our underlying goal of making consumer demand more responsive
Questions?
Future Work

• SBEF can have bad partitions
  • Partitioning scheme that supports goals of mechanism?

• Use partitions for optimization?

• Elicitation of demand profiles