Second-best pricing for incomplete market segments: Applications to electricity pricing

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Most retail electricity customers do not face LMPs

(source: wikipedia)

Policy-makers are often reluctant to have them do so

"As counseled by CPUC staff, the CAISO sought to minimize complexity and time-period variations when evaluating potential TOU periods and structures." (CAISO, 2016)

"la CRE considère qu'afin de répondre au mieux aux attentes des différentes parties prenantes, les tarifs d'utilisation des réseaux doivent concilier les objectifs suivants:

- *Efficacité : un signal tarifaire reflétant au mieux les coûts engendrés sur les réseaux par chaque catégorie d'utilisateurs permet d'optimiser les besoins d'investissements à long terme [...]*
- *Lisibilité : le niveau de complexité des tarifs doit être adapté au type d'utilisateur du domaine de tension considéré."*

(CRE, délibération TURPE 6, 2021)

This work

Research question: *How simple should simple rates be?*

Overview of results

This paper develops a theoretical framework to design simple price schedules which is:

- Easy to implement: computations use basic machine learning techniques and scale easily to large dataset;
- Versatile: a large family of exogenous constraints (e.g. arising from technological or political considerations) can be seamlessly enforced.

Overview of results

This paper develops a theoretical framework to design simple price schedules which is:

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Numerical application to California shows that optimal TOU rates can be unstable over time as the share of solar generation increases. Comparing the period 2011-2014 to the period 2015-2018, the highest-price period has become much narrower (and expensive) and off-peak solar hours have emerged during the winter and the spring.

(Incomplete) literature review

- **Welfare metrics and second-best problems:** Dupuit (1844) ; Ramsey (1927) ; Boiteux (1951) ; Harberger (1964,1971) ; etc.
- **Incomplete markets:** Radner (1968, 1972), Sharpe (2011) ; etc.
- **Imperfect pricing and taxation:** this work closely relates to Jacobsen et al. (JPE, 2020).
- **Applied work on electricity pricing:** Borenstein and Holland (2005) ; Holland and Mansur (2006) ; Borenstein (2013) ; Faruqui and Sergici (2010) ; Wolak (2011); Jessoe and Rapson (2013) ; Ito et al. (2013) ; Ito (2014) ; Borenstein and Bushnell (2019) ; Mcrae and Wolak (2019) ; etc.

Outline

1. Theoretical framework
   - Unconstrained case
   - Accounting for exogenous constraints
2. Application to California
3. Conclusion

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Framework

Electricity as an economic commodity (in the Arrow-Debreu sense) is defined as a kWh delivered:

- at a given **time** (e.g. hour h) ;
- at a given **location** (node of the grid);
- under certain **contingencies** (weather, unplanned outages, etc).

We consider a set of J such commodities, with $J >> 1$.

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Because the market segment of interest is only a fraction of the whole market:

- price rigidities do not compromise market clearing;
- supply costs are assumed (mostly for simplicity) to be exogenous with constant returns-to-scale.

First-best benchmark and deadweight loss

We denote $(p_1^*, ..., p_J^*)$ the vector of first-best prices, that is the vector of marginal costs of supply (at the optimum consumption levels).

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Under standard assumptions, a second-order Taylor approximation of the deadweight-loss arising because of the use of suboptimal prices $(p_1, ..., p_J)$ is:

$$-\frac{1}{2}\sum_{i=1}^{J}\sum_{j=1}^{J}(p_i - p_i^*)(p_j - p_j^*)\frac{\partial x_i}{\partial p_j}$$

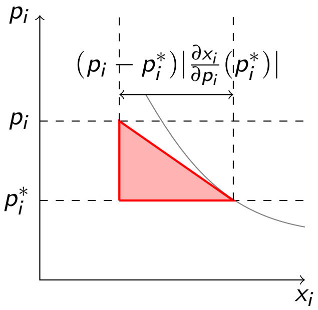
In a partial equilibrium framework, x_i denotes the standard indirect demand function.

Independent commodities special case

When Arrow-Debreu commodities are independent (i.e. $\partial_j x_i = 0$ for $i \neq j$), the deadweight loss expression simplifies to:

$$-\frac{1}{2}\sum_{i=1}^{J}(p_i - p_i^*)^2 \frac{\partial x_i}{\partial p_i}(p_i^*)$$

which is simply a sum of deadweight loss (Harberger) triangles:



Second-best setting

We assume that the vector $(p_1^*, ..., p_J^*)$ is not charged to consumers for a variety of constraints $\mathcal{C}$ (e.g. willingness to charge a simple price schedule). Assuming the rate designer relies on linear prices, he has to solve a second-best problem:

$$\min_{\mathbf{p}} -\frac{1}{2}\sum_{i=1}^{J}\sum_{j=1}^{J}(p_i - p_i^*)(p_j - p_j^*)\frac{\partial x_i}{\partial p_j}(\mathbf{p}^*)$$
$$\text{s.t.}$$
$$\text{constraint } \mathcal{C}$$

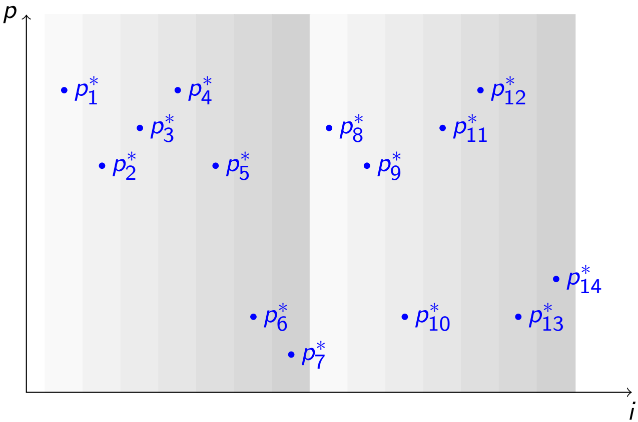
Second-best problem of interest (unconstrained case)

We start by considering the second-best problem defined by:

$\mathcal{C}$: the rate designer may only use an exogenously given number N of distinct prices in his rate schedule.

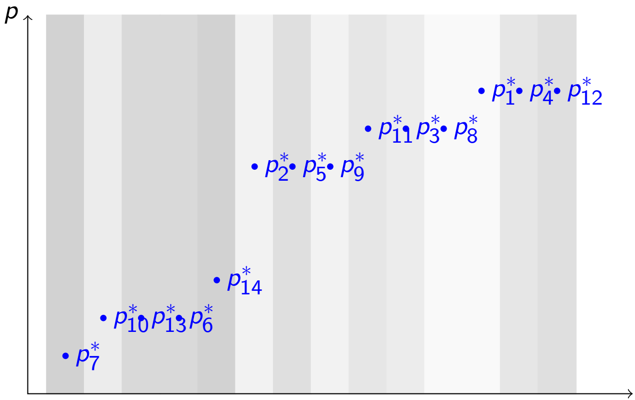
Independent commodities

Simplifying assumption: commodities are independent (i.e. for $i \neq j$, $\frac{\partial x_i}{\partial p_j} = 0$) (for more clarity the graph further assumes $\frac{\partial x_i}{\partial p_i} = 1$ for all i).



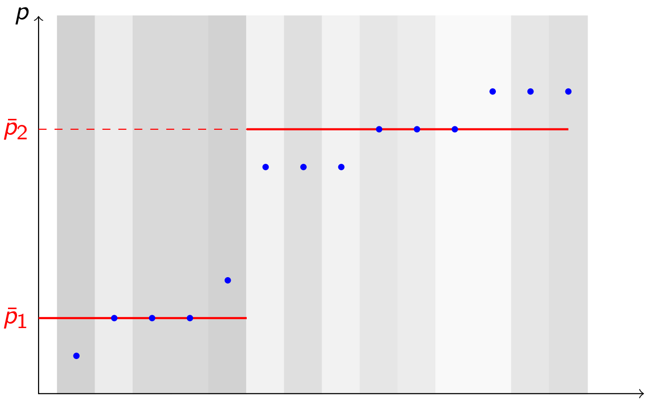
Independent commodities

1. Build the inverse cumulative distribution of first-best prices.



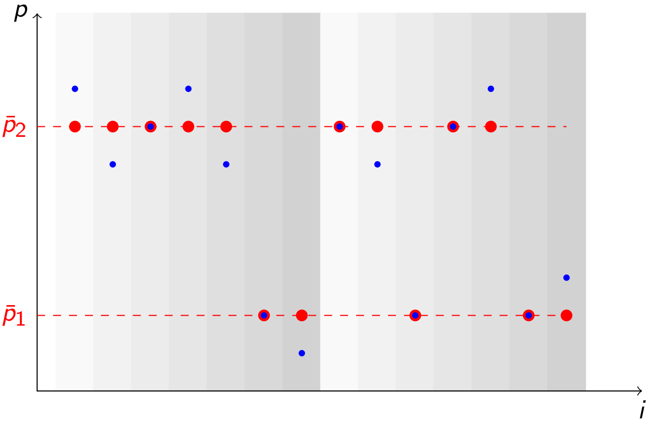
Independent commodities

2. Approximate it by a N-step function ($N = 2$ below).



Independent commodities

3. Obtained price schedule.



Accounting for exogenous constraints - Motivation

So far, we only imposed a single "simplicity" constraint that prevents the rate designer from using more than N prices in his rate schedule. Practical, technical or political considerations may however translate into a much wider family of exogenous constraints.

It turns out that our framework can seamlessly account for constraints of the type *"commodity i must be sold at the same price as commodity j"*. This family of constraints include important applications such as:

- Geography: one may want the rate schedule to be homogenous over wide geographical areas;
- Time: rate stability over full months or weeks may be imposed;
- Contingencies: one may want to minimize the number of contingencies upon which prices can exhibit stochastic variations.

Formalization of additional second-best constraints

We enrich constraint $\mathcal{C}$ as follows:

Assumption

The additional constraints on feasible second-best prices may be formalized as the existence of a finest partition $\underline{s} \equiv \{\underline{S}_1, ..., \underline{S}_M\}$ *that must be a possible refinement of the partition that ends up defining the optimal sets of composite commodities.*

In other words, instead of optimizing on the full set of N-set partitions $\mathcal{S}_N^J$ of the Arrow-Debreu commodities, we now optimize the second-best rate schedule over the following set:

$$\underline{\mathcal{S}}_N^J \equiv \{s \in \mathcal{S}_N^J \,|\, \forall m \in \{1, ..., M\}, \{i_1, i_2\} \in \underline{S}_m \Rightarrow s(i_1) = s(i_2)\} \subset \mathcal{S}_N^J$$

Solution of the enriched second-best problem

Maintaining the assumption of independent commodities and denoting:

$$\hat{p}^*_m \equiv \frac{\sum_{i \in \underline{S}_m} \frac{\partial x_i}{\partial p_i} p^*_i}{\sum_{i \in \underline{S}_m} \frac{\partial x_i}{\partial p_i}} \; ; \; W_m \equiv \sum_{j \in \underline{S}_m} \left| \frac{\partial x_j}{\partial p_j} \right| \text{ and}$$

$$\hat{G}^{-1}(z) = \sum_{m=1}^{M} \hat{p}^*_m \mathbf{1}_{\sum_{k=0}^{m-1} W_k \leq z < \sum_{k=0}^{m} W_k}$$

we have:

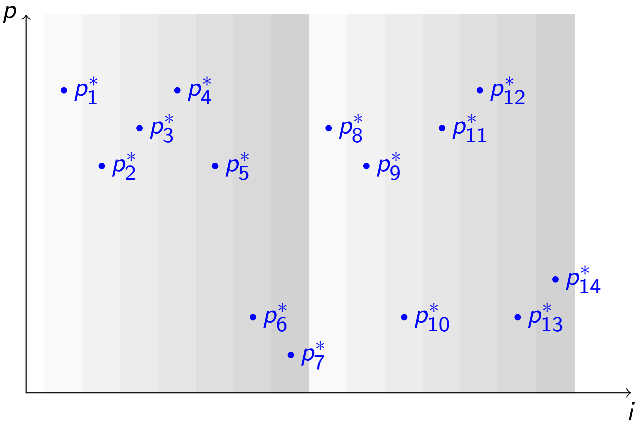
Proposition

The second-best price schedule $(\bar{p}_1, ..., \bar{p}_N)$ is given by the N-step function that best approximates $\hat{G}^{-1}$, when errors are penalized in a quadratic fashion. Welfare losses may be decomposed as the sum of:

- *A first term $\frac{1}{2} \sum_{m=1}^{M} \sum_{j \in \underline{S}_m} \left(\hat{p}^*_m - p^*_j \right)^2 \frac{\partial x_j}{\partial p_j}$ measures the welfare losses arising because of the exogenous constraint of enforcing a finest partition of Arrow-Debreu states.*
- *A second term, consisting in the remaining welfare losses, measures the additional inefficiencies arising because of the limited number of prices used in the rate schedule.*

Graphical intuition

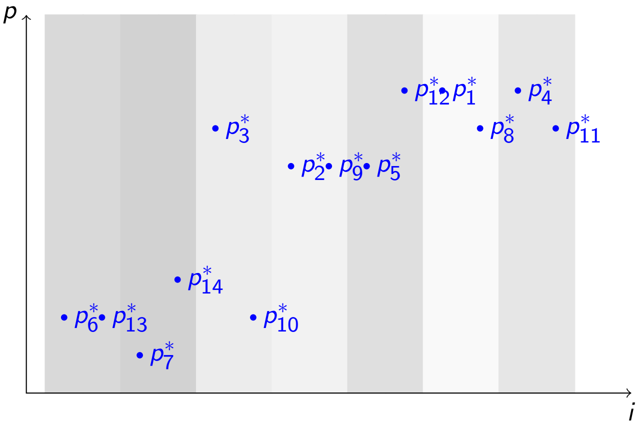
We go back to the previous example and seek to further enforce the constraint that the price schedule should be constant for a given day within the week (e.g. the same prices should apply on Mondays):



Graphical intuition

1. Build auxiliary objects based on the assumed finest partition.

$\Rightarrow$ welfare losses induced by the finest partition



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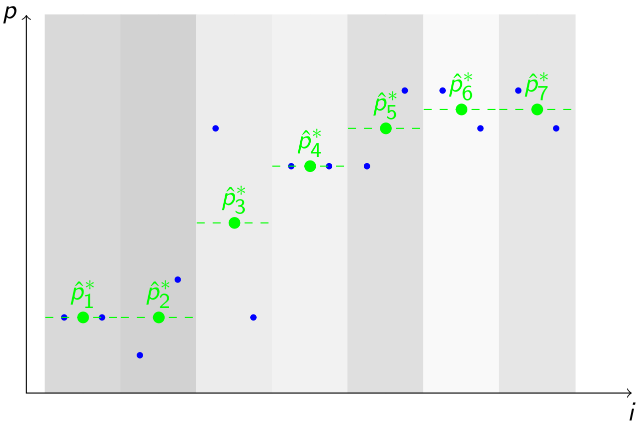
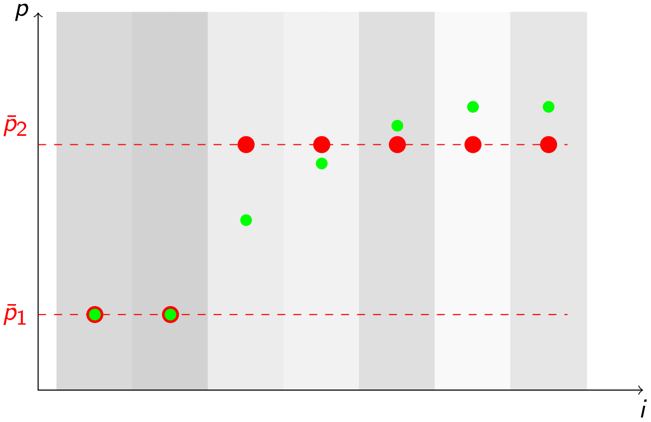


Graphical intuition

2. Approximate it by a N-step function ($N = 2$ below)

$\Rightarrow$ additional welfare losses induced by the limited number of prices.



Graphical intuition

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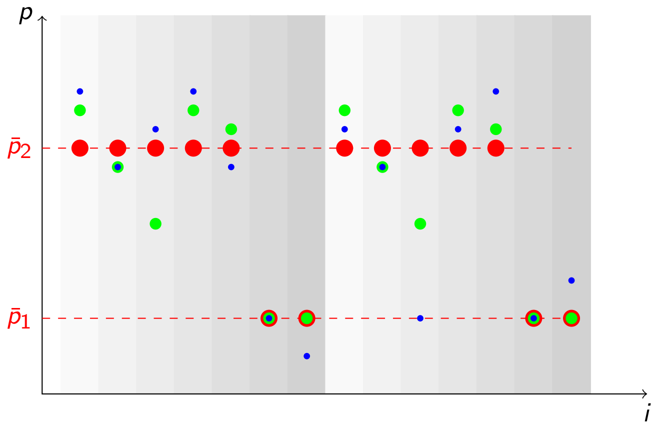


Outline

Data

We focus on the service area of the three main IOUs (PG&E, SCE and SDG&E) between 2011 and 2018 and recover hourly prices (DLAP LMPs) and quantity data from CAISO website.

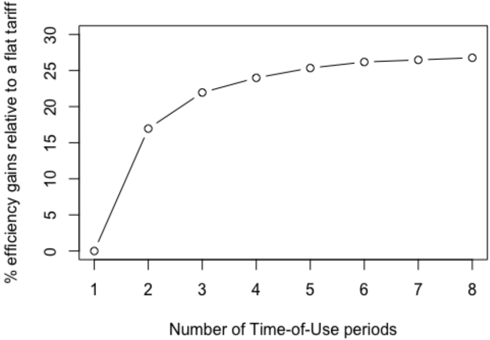
Variable		Mean (std)	Min	Max
PG&E	DLAP price ($/MWh)	36.2 (18.8)	-17.3	946.4
	TAC load (GW.h)	11.5 (1.9)	7.8	21.3
SCE	DLAP price ($/MWh)	37.0 (21.9)	-28.6	1000.0
	TAC load (GW.h)	11.9 (2.6)	7.5	25.8
SDG&E	DLAP price ($/MWh)	38.1 (23.0)	-71.2	1007.5
	TAC load (GW.h)	2.3 (0.5)	1.4	4.7
Number obs.	70128			

Summary statistics (period 2011-2018)

Assumptions

- we use DLAP day-ahead prices as a proxy for the distribution of first-best prices $\mathbf{p}^*$;
- we consider each year to be a different random realization of possible contingencies and divide the data in two samples: 2011-2014 and 2015-2018;
- for simplicity, we assume Arrow-Debreu commodities to be independent;
- we enforce a finest partition that can discriminate between months, types of day (weekends vs working days) and hours of the day. In particular, the TOU rate is assumed to be the same for the three IOUs.

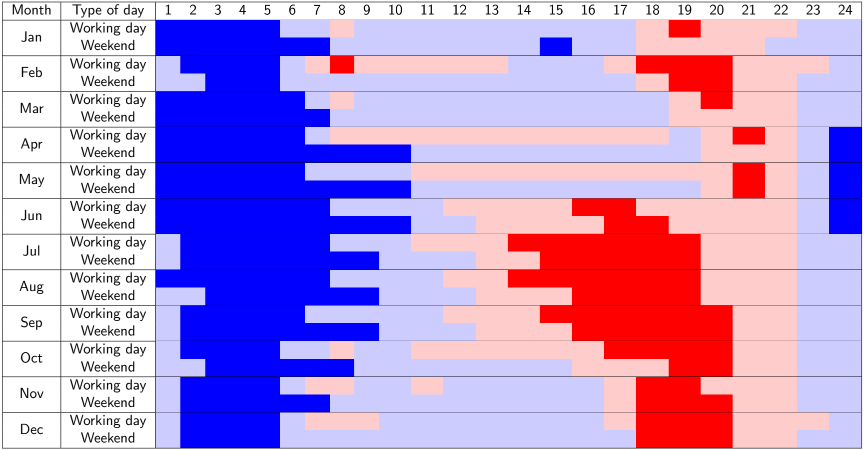
1. No need for complex TOU tariffs



Efficiency gains from increasing the number of Time-of-Use periods (2015-2018)

⇒ *achievable efficiency gains achievable with TOU rates are limited.*

2. An impressive on-going shift in the structure of supply costs - California-wide optimal TOU rate 2011-2014



Obtained California-wide TOU tariff (isoelastic demand, 2011-2014 data)

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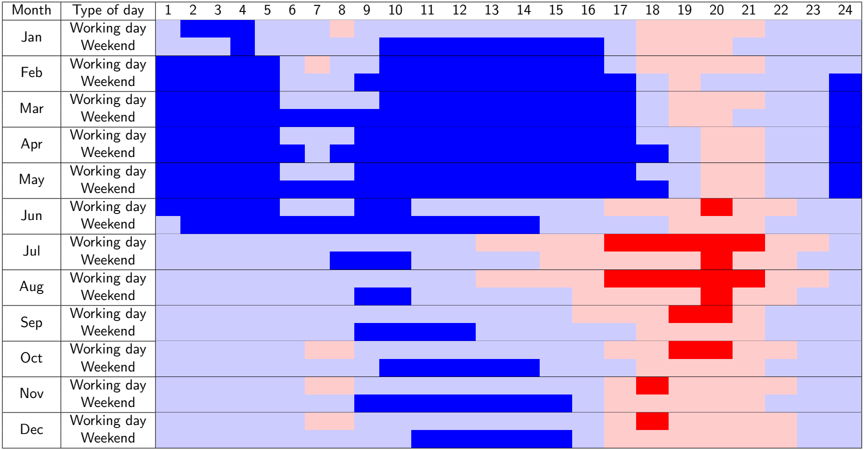

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3. Exploring different margins of efficiency gains

1. Critical-peak pricing achieves significant efficiency gains:
   Instead of a four-tier TOU rate, one could alternatively implement a simple tariff with four prices consisting in:
   - critical-peak events called at most a given number of hours per year (e.g. 200 hours);
   - a three-period TOU rate for the rest of the year.

   $\Rightarrow$ relative to a three-period TOU rate, implementing critical-peak events increases efficiency by about 40% while adding a fourth TOU period only yields of $3-4\%$ improvement.

2. Limited gains from spatial differentiation relying on zones:
   - Designing an IOU-specific TOU rate instead of a California-wide rate decreases deadweight losses by only about 1%;
   - Using smaller zones, namely SLAPs, enables higher but still modest gains (up to 7% when focusing on 2015-2016 only).

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Areas for further research

- Do the empirical results for California extend to other power systems as well?
- Longer-term perspective:
    - how will the first-best prices distribution evolve with a changing electricity mix?
    - can simple tariff still do a good job at approximating this distribution?