Dynamic pricing of electricity: money on the table?

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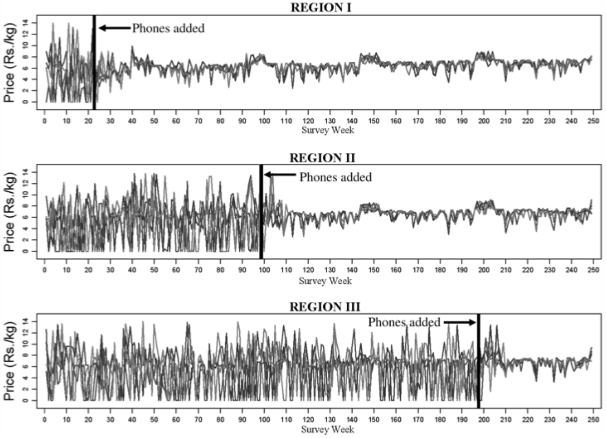
> The law of supply and demand works well with much of the world's commerce. Why not apply this law to consumer purchases of electricity? Improbable though this may seem, extensive advances in computation and communication could allow a modified supply-and-demand electrical system to become operational in a few years. *–Schweppe et al. (1982)*

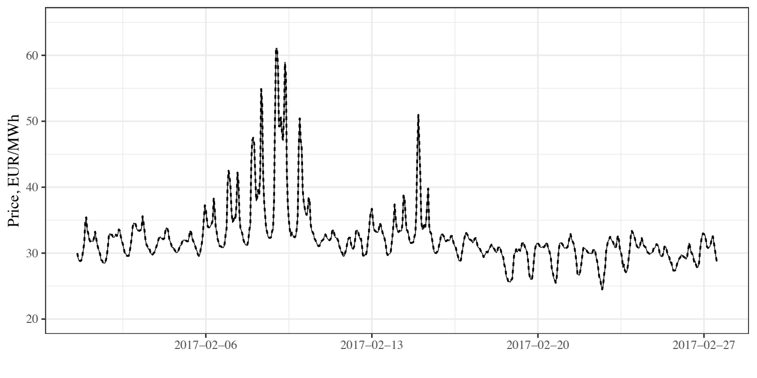
Reminder: ICT can change the equilibrium



Fish prices and mobile phone service in Kerala.

Robert Jensen (2007)

A puzzle: If fish, why not electricity?



Nordic electricity prices in February 2017.

To solve the puzzle: Structural exercise with big data

- **Quantify the money** on the table
  - Answer to Joskow (2012): *"Is the gain large enough to cover the additional costs of smart meters and associated information and automated distribution technology?"*
- **Evaluate short-run equilibrium impacts**
  - Borenstein and Holland (2005): *short-run distributional impacts of added dynamic pricing are ambiguous*
  - We show when consumers gain and when they lose, with empirical examples of both
- Novel use of an **underutilized data** set
  - Electricity market bid data only recently taken in to use (e.g. Fabra and Reguant 2014).

Long-run impacts: e.g. Borenstein (2005), Holland and Mansur (2006), Allcott (2012) and Léautier (2014).

Prerequisites for benefits: Price signals and investments

Dynamic pricing and flexible technologies can:

1. Increase the quantities traded
2. Allocate supply to the highest demand values
3. Reduce rent-seeking behavior

We use over 160 million price-quantity bids to quantify the market equilibrium impacts of points 1. and 2. on the day-ahead market.

See e.g. Bulow and Klemperer (2012).

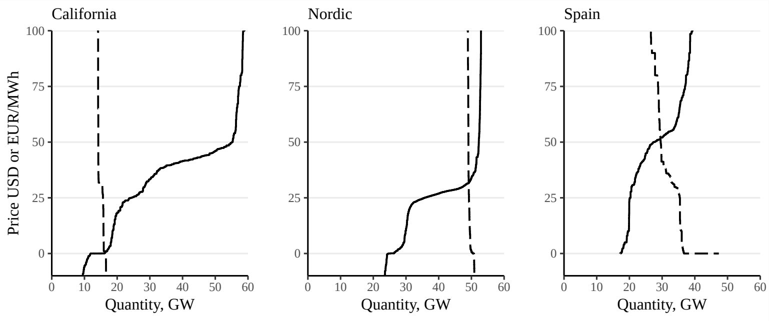
Institutions and data

Comparison of three advanced electricity markets

		California	Nordic	Spain
Electricity generation	TWh	216.7	411.4	275.6
Solar	%	16 %	0.2 %	5 %
Wind	%	6 %	10 %	18 %
Hydro	%	20 %	54 %	8 %
Wholesale market value	billion $/€	7.7	12.1	14.4
Residential electricity tariff	c/kWh	19.65	20.85	23.83
Number of households	million	14.7	11.8	18.3
Share of smart meters	%	85	80	91

Table 1: Summary statistics for the markets in 2017 (Eurostat, EIA).

Data set: Bid curves



Demand and supply bid curves for noon 3 Apr 2017.

- In total 160+ million bids from California, the Nordic market and Spain from the years 2002–2018.
- Each bid consists of a price and quantity pair for one hour.

Clean-up: From raw data to system level bids

- Data obtained from the market operators: CAISO (California), Nord Pool (Nordic), and OMIE (Spain/Iberian).
- We convert raw bid data to hourly "system" area bids in the day-ahead energy only market.
- CAISO most complex, we need to account for:
  - Nodal pricing scheme that includes transmission constraints.
  - Multi-market bidding (energy and ancillary services).
  - Several alternative schedules.
  - Virtual bidding.
- Processing of Nordic and Spanish bid data simpler; operator data more directly applicable for our needs.

Approach

Approach

1. Structural model to replicate market outcomes, hour-by-hour in the day-ahead market (P, Q)
   - We obtain comparable "system prices" for the three markets
2. Counterfactual outcomes, for varying shares of price responsive technologies
   - Efficiency, scale, and distributional effects

- **Advantages**: obtain cross-market comparisons; no need to simulate or resort to the machinery of statistical inference
- **Shortcomings**: short-run effects only, bids taken as they are

Structural model: The same as in market price computation

Surplus maximization, one hour:

Given demand bids $(p_i, Q_i)_{i \in \mathcal{D}}$ and supply bids $(p_j, Q_j)_{j \in \mathcal{S}}$ for a single time period t, we solve:

$$\begin{aligned} \max_{d_i, s_j} \sum_i p_i d_i - \sum_j p_j s_j \\ \text{s.t.} \quad d_t = \sum_i d_i, \quad 0 \le d_i \le Q_i, \ \forall i, \\ s_t = \sum_j s_j, \quad 0 \le s_j \le Q_j, \ \forall j, \\ d_t - s_t = 0. \end{aligned}$$

The shadow prices of the balance constraint $d_t - s_t = 0$ give the market prices.

Counterfactuals: Add flexibility to the model

Surplus maximization, several hours:

$$\max_{d_i, s_j} \sum_t \left[\sum_i p_i d_i - \sum_j p_j s_j \right]$$

$$\text{s.t.} \quad d_t = \sum_i d_i, \quad 0 \le d_i \le Q_i, \ \forall i,$$

$$s_t = \sum_j s_j, \quad 0 \le s_j \le Q_j, \ \forall j.$$

We relax the balance constraint with a possibility to "trade" between the hours with some capacity limit $\bar{y}$:

$$d_t - s_t = y_t, \quad \forall t,$$

$$-\bar{y} \le y_t \le \bar{y}, \quad \forall t,$$

$$\sum_t y_t = 0.$$

Added flexibility: It's like trade

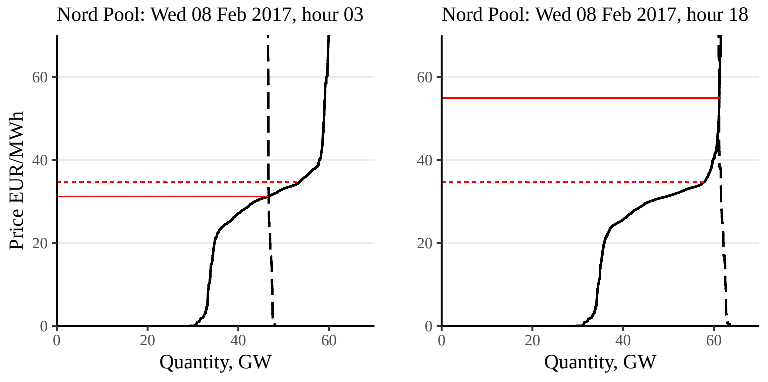


Figure 1: Buy cheap (left), sell dear (right) – But prices converge!

Results

Private arbirage gains over time: Small on average

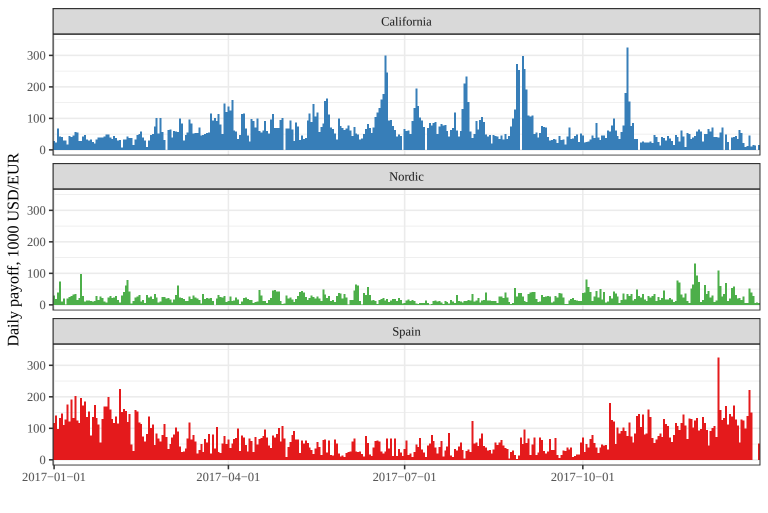


Figure 2: Illustration of the daily arbitrage gains in 2017.

Private gains: Little money on the table

Table 2: The sum of arbitrage gains over the year in million U.S. dollar or euro, not including any investment costs or efficiency losses with 1 GW of flexibility (ca. 1 million households).

	California	Nordic	Spain
2011		11.5	27.1
2012		12.4	36.6
2013		11.4	43.6
2014		10.7	37.8
2015	16.2	10.0	33.3
2016	15.6	11.2	23.6
2017	23.8	8.6	26.5
2018	30.2	13.7	24.9

E.g. in California in 2017 the gain would be 23.8 USD per kW.

Increase of flexibility: Arbitrage gains disapper

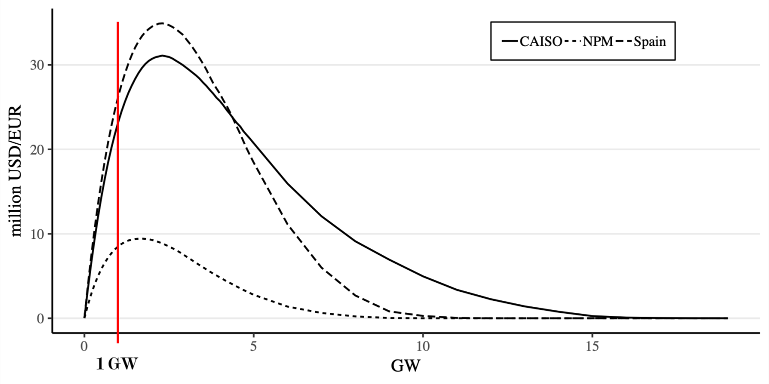


Figure 3: The sum of arbitrage gain over the year 2017 by market area as the capacity of the flexible technology increases.

But consumer surplus can increase: the Nordic market

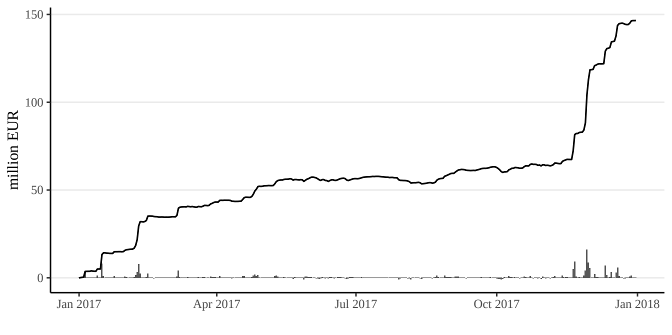


Figure 4: Daily gain/loss for all consumers (bars) with 1 GW of flexibility and a cumulative sum over the year 2017 (line) in the Nordic market.

Or consumer surplus can decrease: California

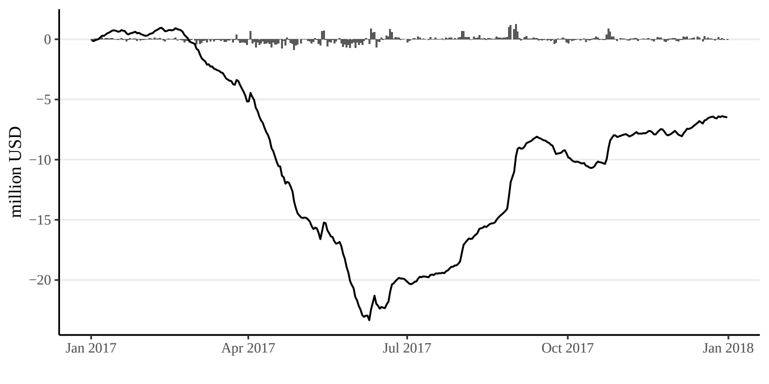


Figure 5: Daily gain/loss for all consumers (bars) with 1 GW of flexibility and a cumulative sum over the year 2017 (line) in California.

What explains the differences between the markets?

Convexity of supply

- Compressing load realizations with convex supply: consumers benefit
- The Nordic case!

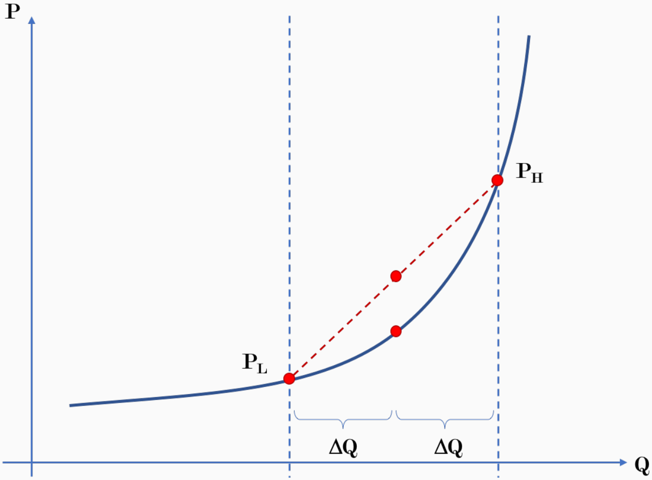
Concavity of supply

- Doing the same with concave supply: producers benefit
- Spring in California!

Spain somewhere in between.

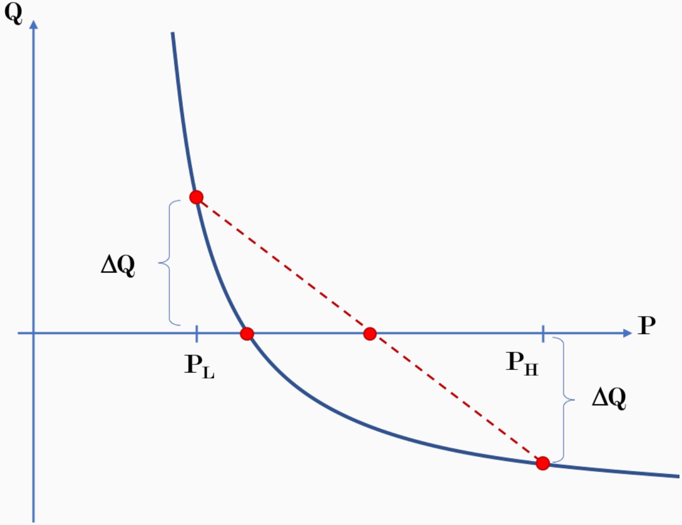
Borenstein and Holland (2005) show this in a theoretical setting. Also, cf. with Bulow and Klemperer (2012).

Illustration: Convex supply – inelastic demand



Single supply curve, inelastic demand varies between high and low.

Tool for analysis: Excess demand curve



Excess demand curves, starting from free trade.

Empirical evidence: we can see this in our data

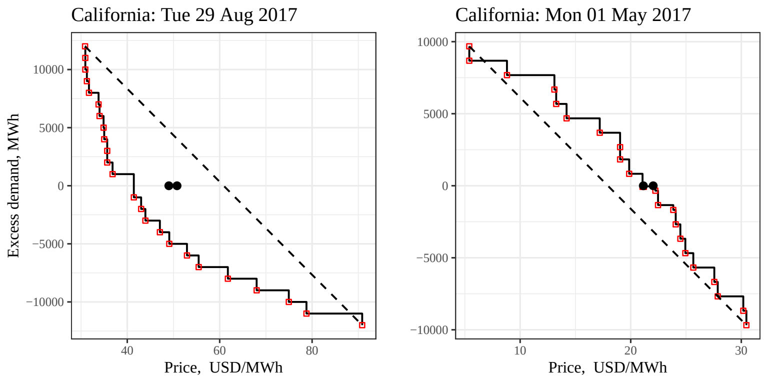
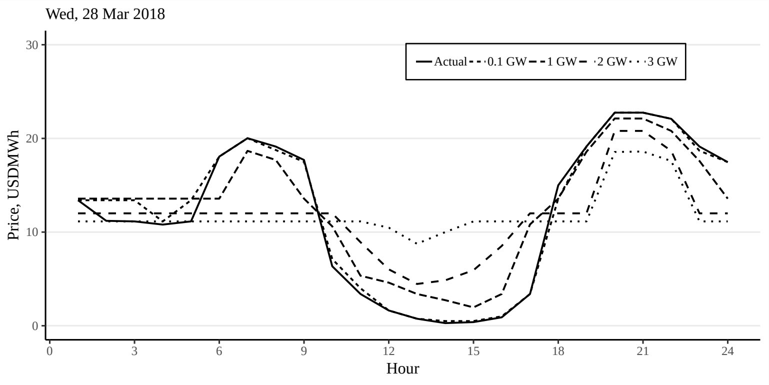


Figure 6: Excess demand curves for two days in California. Consumers benefit if the daily excess demand curve is convex (left panel) and lose if the curve is concave (right panel).

Concave case: Taming the duck in California



The duck: Hourly prices in California for one sunny day in 2018.

Surplus changes: Large variation over the years

Table 3: Change in consumer surplus as a sum over the year in million U.S. dollar or euro.

	California	Nordic	Spain
2011		-17	106
2012		465	128
2013		176	130
2014		86	77
2015	13	147	50
2016	5	305	41
2017	-6	146	32
2018	33	260	-5

Efficiency gains: No money on the table

Table 4: Change in efficiency in million U.S. dollar or euro.

	California	Nordic	Spain
2011		5.4	6.1
2012		6.7	8.6
2013		4.3	8.8
2014		3.2	9.3
2015	1.6	3.7	8.5
2016	3.0	4.3	6.2
2017	5.6	3.4	6.3
2018	5.6	5.9	6.1

Change in efficiency in 2017 is (0.07, 0.03, 0.04) % compared to the wholesale energy bill in California, Nordics or Spain.

Holland and Mansur (2006) find 0.08 % for a one third adoption of RTP in PJM.

Discussion

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- **Little or no money on the table**: Flexibility and dynamic pricing would have added little to market efficiency or the investors' chests
  - Why would professional operators leave money on the table?
  - Yet retail pricing inefficiencies (e.g. Wolak 2018) may offer larger rewards, not fully captured here.
- But flexibility may cause **large shifts in surplus** between producers and consumers, at least in the short-term
  - Concave case: Over-capacity kept running.
  - Convex case: Shortage of capacity.