The (smart) technology effect

Consumers, not producers, benefit from more efficient trade in electricity markets

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13th Conference on the Economics of Energy and Climate, June 2022

Fish

Technology effect: fish example

Localized markets

- no communication when out in the sea: uncoordinated landings
- beach markets: price dispersion

Integrated markets

- adoption of mobile phones: coordinated landings
- price dispersion declines, allocations become more efficient

Jensen 2007

Similar studies: Aker 2020; Allen 2014; Steinwender, 2018

In Electricity

Localized markets

- hours of the day
- intermittent supplies, demand variation: price dispersion

Integrated markets

- new technologies: smart devices, storage technologies.
- technologies serve the same purpose: buy/use energy when prices are low and sell/don't use it when prices are high

price dispersion declines, allocations become more efficient

Question

Technologies remove barriers to trade but do consumers benefit?

- Is the price level lower in the end?
- Is removing price dispersion good or bad for consumer welfare?

Relevant in electricity

- new technologies are mandated by policies (FERC 2018; EU directives 2009/2012; RTP deployment in Spain 2015).

This paper: how do the technologies impact the consumers through changes in the market equilibrium?

Approach

1. We start with simple price theory for comparing localized trade and free trade
   - Price dispersion
     - EV owner benefits from price dispersion!
   - Price correlation
     - EV owner benefits if supplies are correlated with needs
   - Price level
     - EV benefits from concave excess demand

Approach

1. We start with simple price theory for comparing localized trade and free trade
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     - EV benefits from concave excess demand
2. Empirical quantification
   - micro-data on 160 million of bids from electricity wholesale markets in California, Nordics, and Spain
   - system equilibrium in each market: replication from bids, and a counterfactual equilibrium with more efficient trade
   - Empirical assessment of the three channels from an experiment: $1GW$ of "efficiency"

Results

Consumer benefits

- social value of additional arbitrage is small
- consumer benefits by multiple factors larger

source of benefits

- due to price level changes, not price dispersion
- Results consistent across markets

differences between markets

- price-level change is consistently the key channel for consumer benefits
- the mechanism is very different across the three markets

Literature

Trade

- Jensen, 2007; Aker, 2010; Allen, 2014; Steinwender, 2018
- market integration in electricity: the impact of data centers, even cryptocurrency mining. Multimarket approach needed

Price stabilization

- Wright, 2001; Newbery and Stiglitz, 1979
- in electricity: Ambec and Crampes 2021

Storage

- e.g., Butters, Dorsey and Gowrisankaran 2021; Karaduman, 2021

Simple price theory

Localize markets:

$i \in \mathcal{I}$ be an index for a local market

$$\underbrace{\big(D(p) + d_i\big)}_{\equiv D_i(p)} - \underbrace{\big(S(p) + s_i\big)}_{\equiv S_i(p)} \equiv X_i(p).$$

finite local price p_i such that $X_i(p_i) = 0$ for all $i \in \mathcal{I}$

Free trade:
one price for all markets $\sum_{i \in \mathcal{I}} X_i(p) = 0$

$$\Rightarrow D(p) - S(p) = \overline{x}$$

where $\overline{x}$ is the mean of the local market conditions $x_i \equiv s_i - d_i$

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Free trade $\rightarrow$ localized markets: mean-spreserving spread of $\overline{x}$

Gaussian structure on $x = s - d$:

$$\begin{pmatrix} s \\ d \end{pmatrix} \sim \mathcal{N}\left(\begin{pmatrix} 0 \\ 0 \end{pmatrix}, \begin{pmatrix} \sigma_s^2 & r\sigma_s\sigma_d \\ r\sigma_s\sigma_d & \sigma_d^2 \end{pmatrix} \right)$$

Consumer surplus Let $\mathcal{D}(v,d) \equiv D(v) + d$ for short

$$\mathbb{E}W = \int_{x\in\mathbb{R}} \int_{d\in\mathbb{R}} \int_{v\geqslant p(x)} \mathcal{D}(v,d)dG(d|x)dF(x),$$

Consumer surplus Expanding

$$\mathbb{E}W = \int_{x \in M} \underbrace{\int_{v \geqslant p(x)} (D(v) + ax) dv}_{\equiv U(x)} \, dF(x)$$

where

$$a \equiv \frac{r\sigma_s\sigma_d - \sigma_d^2}{\sigma_s^2 + \sigma_d^2 - 2r\sigma_s\sigma_d}$$

Free trade:

$$\mathbb{E}W = U(\overline{x})$$

Autarky:

$$\mathbb{E}W = \int_{x \in M} U(x) dF(x)$$

Proposition

(Price dispersion) *Assume that $D(p)$ and $S(p)$ are linear and $r \geq \frac{\sigma_d}{\sigma_s}$. Then, it holds for the consumer surplus that $\mathbb{E}W > U(\overline{x})$.*

Intuition: consumer can optimize.
In fact, when $r = \frac{\sigma_d}{\sigma_s}$ and convexity $U'' = -p'(x)(1-\rho)$ depends only on passthrough $\rho = \frac{1}{1+\frac{\varepsilon_d}{\varepsilon_s}}$.

Proposition

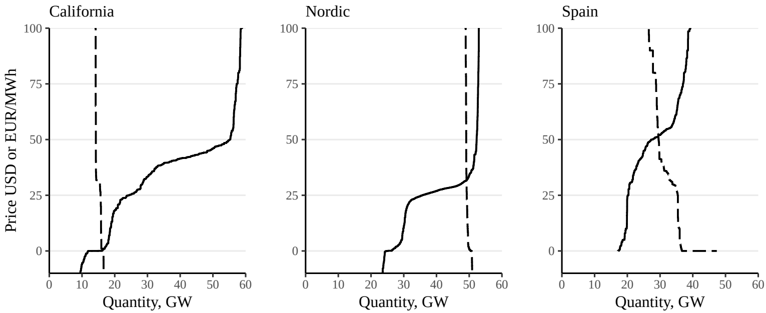
(Price correlation) *In proposition 1, if* $\frac{\varepsilon_d}{\varepsilon_s} \to 0$*, then* $\mathbb{E}W > U(\overline{x})$ *if and only if* $r > \frac{\sigma_d}{\sigma_s}$.

Proposition

(Price level) *Assume it holds that $X''(p) = D''(p) - S''(p) < 0$. Then, $\mathbb{E}W > U(\overline{x})$ if $r \geq \frac{\sigma_d}{\sigma_s}$.*

Empirical quantification

Data set: Bid curves



- Three markets with structural differences in existing generation
  - California: biggest in solar
  - Nordics: most hydro
  - Spain: largest share of wind
- 160+ million bids from the years 2015–2020 → transformed into common bidding language (many assumptions)

Table: Bid data descriptives

	Number of bids			Data period	Hours with data
	Demand	Supply	Total		
CAISO	13,372,460	45,095,271	58,467,731	01/01/15–12/31/20	49,080
NPM	30,875,292	45,709,770	76,585,062	01/01/15–12/31/20	52,608
Spain	7,708,735	23,063,787	30,772,522	03/03/15–12/31/20	52,470

Notes: Data for some days or hours is missing or has been removed in the preprocessing e.g. because of incomplete or erroneous data.

The approach: three steps

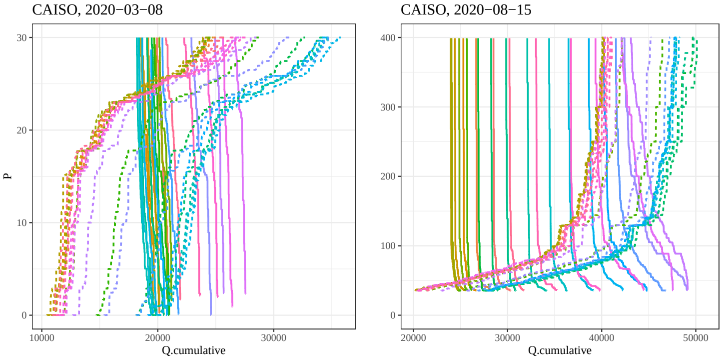
1. run the market-clearing procedures of the power exchanges with actual bids
2. re-run the market clearing with additional capacity for trading
3. regression of outcomes on covariates capturing the three theory channels

Step one: replication from bids

$$\max_{Q^d_{i,h}, Q^s_{j,h}} \sum_{i \in \mathcal{D}_h} p_{i,h} Q^d_{i,h} - \sum_{j \in \mathcal{S}_h} p_{j,h} Q^s_{j,h} \tag{1}$$

$$\begin{aligned} \text{s.t.} \quad Q^d_h &= \sum_{i \in \mathcal{D}_h} Q^d_{i,h}, \quad Q^d_{i,h} \in [0, Q_{i,h}] \\ Q^s_h &= \sum_{j \in \mathcal{S}_h} Q^s_{j,h}, \quad Q^s_{j,h} \in [0, Q_{j,h}], \\ X_h &= Q^d_h - Q^s_h = 0. \end{aligned}$$

Illustration: two days in California



Step two: counterfactuals

$$\max_{Q^d_{i,h}, Q^s_{j,h}} \sum_{h \in \mathcal{H}} \left[\sum_{i \in \mathcal{D}_h} p_{i,h} Q^d_{i,h} - \sum_{j \in \mathcal{S}_h} p_{j,h} Q^s_{j,h} \right], \tag{2}$$

where we relax the hourly supply–demand balance constraints with a possibility to "trade" a net quantity Y between the hours:

$$X_h = Q^d_h - Q^s_h, \quad \forall h,$$
$$-Y \leq X_h \leq Y \quad \forall h,$$
$$\sum_{h \in \mathcal{H}} X_h = 0.$$

Illustration: free trade

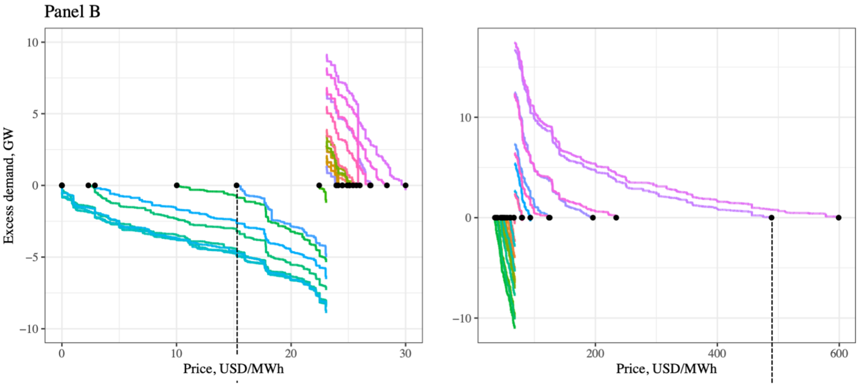
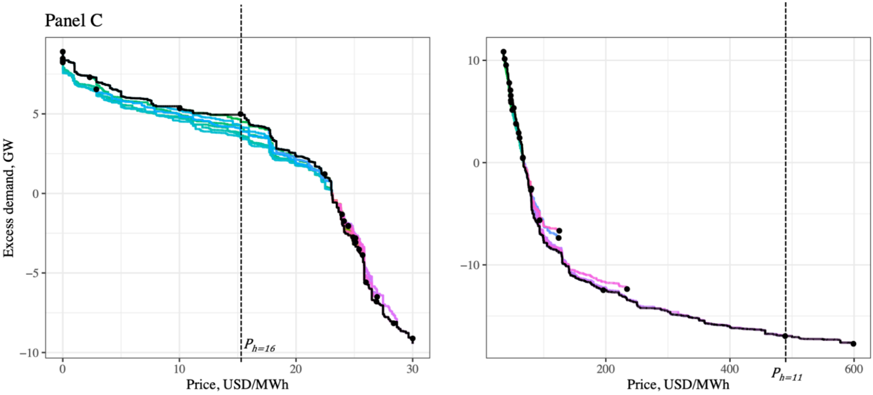


Illustration: free trade, excess demand for the day



Results

Results: the technology impact

Table 1: Impact of 1 GW flexible technology

		Q	ΔQ	P	ΔP	Consumer surplus	Market welfare	Gain from trading
Area	Obs.	GW		\$/MWh or €/MWh		Change in M\$ or M€ per year		
California	All	28.075	-0.004	32.14	-0.22	114.05	6.33	56.05
	Consumer gain	29.035	0.009	35.78	-0.53	211.03	6.65	63.11
	Consumer loss	26.282	-0.029	25.35	0.36	-67.13	5.71	42.87
Nordic	All	41.241	0.004	28.06	-0.23	156.43	3.91	9.92
	Consumer gain	42.871	0.008	27.47	-0.56	291.20	4.17	10.51
	Consumer loss	38.389	-0.004	29.10	0.34	-79.46	3.44	8.87
Spain	All	26.741	-0.067	46.96	-0.06	48.79	6.62	24.87
	Consumer gain	26.364	-0.071	45.18	-0.34	110.22	6.82	25.35
	Consumer loss	27.384	-0.060	50.00	0.42	-56.23	6.27	24.06

Notes: Table reports the mean values of the hourly data for volume (in GW) and price (in € or $ per MWh), change in volume (in GW) and change in price (in € or $ per MWh). The welfare measures are mean annual changes, and the Table presents change in consumer surplus, change in the total surplus in the market, and the private gain from trading (millions of U.S. dollars or euro). Data as reported in Table A.5.

Results: Connecting to theory

Outcome variables

- (retail) consumer surplus changes, daily
- measured from the bid curves

Covariates

- Price dispersion channel: elasticities of demand and supply from the bids
- Price correlation channel: variation of demand $\sigma_{d,t}$ and supply $\sigma_{s,t}$ as variation of the respective daily quantities at price fixed
- Price level channel: convexity of excess demand

Results: California

Table: California, 1 GW

Dependent Variable:			Consumer surplus		
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Convexity	0.225 (0.002)	0.224 (0.002)	0.224 (0.002)	0.223 (0.002)	0.226 (0.002)
Variation, Demand		0.006 (0.006)	0.007 (0.006)	0.013 (0.007)	0.014 (0.007)
Variation, Supply			-0.005 (0.009)	-0.008 (0.009)	-0.011 (0.010)
Correlation				-0.112 (0.050)	-0.062 (0.054)
Passthrough					0.542 (0.285)
Fit statistics					
R^2	0.91202	0.91206	0.91208	0.91230	0.91951
F-test	21,177.5	10,589.8	7,057.6	5,305.1	4,190.4
Observations	2,045	2,045	2,045	2,045	1,840

Normal standard-errors in parentheses

Results: Nordics

Table: Nordics, 1 GW

Dependent Variable:			Consumer surplus		
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Convexity	1.07 (0.010)	1.08 (0.011)	1.07 (0.011)	1.07 (0.011)	0.747 (0.013)
Variation, Demand		-0.024 (0.013)	-0.047 (0.014)	-0.051 (0.014)	-0.014 (0.012)
Variation, Supply			0.137 (0.034)	0.124 (0.035)	0.106 (0.029)
Correlation				0.093 (0.075)	0.086 (0.063)
Passthrough					-24.0 (0.687)
Fit statistics					
R^2	0.82855	0.82882	0.83012	0.83024	0.89220
F-test	10,583.8	5,299.3	3,563.9	2,673.9	3,530.8
Observations	2,192	2,192	2,192	2,192	2,139

Normal standard-errors in parentheses

Results: Spain

Table: Spain, 1 GW

Dependent Variable:			Consumer surplus		
Model:	(1)	(2)	(3)	(4)	(5)
Variables					
Convexity	0.141 (0.004)	0.151 (0.004)	0.158 (0.004)	0.159 (0.004)	0.154 (0.004)
Variation, Demand		0.029 (0.006)	0.046 (0.006)	0.044 (0.006)	0.050 (0.006)
Variation, Supply			-0.055 (0.006)	-0.059 (0.006)	-0.059 (0.006)
Correlation				0.035 (0.022)	0.091 (0.023)
Passthrough					-0.368 (0.048)
Fit statistics					
R^2	0.39454	0.40199	0.42786	0.42855	0.44536
F-test	1,427.1	735.74	545.42	410.03	340.30
Observations	2,192	2,192	2,192	2,192	2,125

Normal standard-errors in parentheses

Economics of the results

Video

Conclusions

Results

- Consumer surplus changes by multiple times more than the total surplus
- The benefit is due to, not because of converging prices, but changes in price levels

Important to understand: technologies is often mandated by policies

Conclusions

Contribution

- Comparison of three major markets. Single market studies typical (Butters et al., 2021, Karaduman, 2020, Reguant, 2014, etc.)
- Benefits from price stabilization literature: Wright (2001); Newbery and Stiglitz (1979), Just et al. (1978)