Do consumers gain when new technologies improve the efficiency of goods trade?

Matti Liski and Iivo Vehviläinen*

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Abstract

This paper points out the basic price theory predictions for the consumer welfare gain from new technologies that improve the efficiency of goods trade. Micro-data on over 140 million of bids from electricity markets in California, Nordics, and Spain reveals that the consumer surplus gain from efficiency improvements follows a markedly different pattern in the three markets. Consistent with the theory, the results can be explained by structural differences in excess demand: its convexity (concavity) is a determinant of consumers' gain (loss).

JEL Classification: D61, D83, F10, Q41, Q48

Keywords: Information technology, frictions, trade, electricity

*Liski (matti.liski@aalto.fi) and Vehviläinen (iivo.vehvilainen@aalto.fi): economics department of the Aalto University and Helsinki Graduate School of Economics. We thank Stefan Ambec, Markku Kallio, Mathias Laffont, Robert Ritz, Geert Van Moer, and participants at seminars in Bern, Copenhagen, Geneva, Hamburg, Helsinki, Munich, Tampere, Paris, Toulouse, and Vaasa for valuable comments and discussions. We thank James Corbishley for research assistance at early stages of this work.

1 Introduction

Information is important for the real economy. The lack of it is a source frictions, distinct from traditional trade costs, leading to allocative inefficiencies in goods trade (Jensen, 2007; Aker, 2010; Allen, 2014; Steinwender, 2018). New technologies improve efficiency if, for example, they allow producers to learn about market conditions in other locations or other times. While the reduction in price dispersion has been well documented in the literature on information frictions in goods trade, little is know about the conditions under which the move towards the law of one price results in final benefits to the consumers. Is it a general pattern that consumers gain when new technologies improve the efficiency of trade? For instance in Jensen (2007), after the adoption of mobile phones, consumers no longer get their fish at occasional bargain prices but yet end up gaining more surplus.

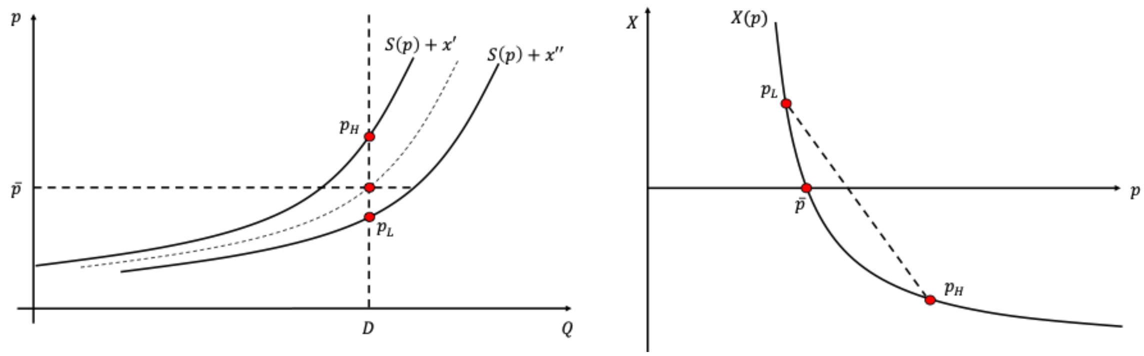
In this paper we start by noting the price theory predictions for the consumer welfare. We build on the notion of excess demand which measures how much trade is missing and how dispersed the prices are across markets that could become one integrated market. A consumer who is not yet exposed to a price likes to face a "price lottery": The option to choose how much to consume under dispersed prices generates a surplus gain.[1] This gain evaporates when frictions generating the price lottery dwindle, but the price level will change as well. Fig. 1 illustrates the level effect with inelastic demand. There are exogenous shocks to supply that, if markets with different shocks remain localized, lead to dispersed prices (left panel). Frictionless trade neutralizes shocks, leading to one price with excess demand across markets vanishing (right panel). However, given that the excess demand is convex in this illustration, the price level decreases with trade and, then, the consumer necessarily benefits from trade.

The excess demand measures how the price level changes with missing trade and therefore it links the consumer welfare to the market rudiments, the shapes of demand and supply. Bids from electricity markets offer these shapes as data, providing access to the sources of excess demand convexity and thereby to the market determinants of the welfare impacts.[2] We use micro-data on over 140 million bids from three electricity

[1]This result follows from elementary microeconomics when preference are quasi-linear – the consumer welfare is convex in prices. The price theory implications of the result were first elaborated by Waugh (1944). The result holds for the indirect utility in general under restrictions on preferences (Turnovsky, Shalit and Schmitz, 1980).

[2]Electricity markets offer a useful laboratory for questions where the microstructure of demand and supply is important. The questions include: pass-through (Fabra and Reguant, 2014), market power

Figure 1: Illustration of convex excess demand



Notes: Demand D is inelastic and supply $S(p) + x$ is elastic with exogenous shock x, resulting in different prices in localized markets. Excess demand $X(p) = D - S(p)$ is drawn for free trade and mean value $x = 0$.

markets to shed light on how "price stability" impacts consumer welfare, a question that has long haunted economists, with little empirical work on the issue.[3]

Electricity markets are impaired by frictions as consumers typically do not respond to short-term price changes. A potential explanation for the unresponsiveness is that overcoming frictions is costly: Information technologies alone are not enough but one must also invest in technologies that allow quantities to change, for instance, through storage technologies. Yet, the technologies to overcome frictions are developing at a rapid pace (Joskow and Wolfram, 2012), changing efficiency and the surplus division between consumers and producers. Our quantification addresses this change.

We quantify the change in surpluses in three day-ahead markets for wholesale electricity — California, the Nordics, and Spain — following from a quantitative experiment where there is 1 GW of additional capacity for efficiency improving quantity reallocations over the hours of any given day. To illustrate, the size of the experiment is roughly equal to the demand response coming from one million households.[4] We replicate first the realized day-ahead market allocations and prices, using a model that interprets how trading institutions in place map the submitted bids to market outcomes in the three markets. We then produce counterfactual market outcomes by taking the actual bids as data and changing the set of activated bids, given the added capacity for efficiency-improving reallocations.[5]

(e.g., Borenstein, Bushnell and Wolak, 2002), complex bidding strategies (Reguant, 2014), contracting (Hortaçsu and Puller, 2008), vertical integration (Bushnell, Mansur and Saravia, 2008), and sequential trading (Ito and Reguant, 2016).

[3] See Wright (2001) for an overview and, for example, Newbery and Stiglitz (1979).

[4] See, for example, Lawrence Berkeley National Laboratory (2017).

[5] The approach does not limit interpretations of who and by what precise technology achieves the

The surplus gain from the experiment follows a markedly different pattern in the three markets. In California, the demand side systematically ends up losing surplus for a significant part of the year. Thanks to the bid data, we can link the explanation of the result to the *concavity of the excess demand*, arising from the production conditions created by the high penetration of solar PV systems. In the Nordics, in contrast, a sizable surplus gain emerges, up to 10% of the total market-level revenue. The result can be linked to the strong *convexity of the excess demand*, driven by production conditions that differ from those in California. The Spanish case is in the middle of the road, with both demand and supply contributing the shape of the excess demand; it comes close to a linear shape.

The results show that improvements in allocative outcomes can benefit or hurt the consumers, as in the case of price controls (Bulow and Klemperer, 2012), but the channels through which new technologies impact consumer surplus are distinct and have received little attention.[6]

Understanding the welfare mechanism is important to policy makers. For example, the adoption of consumer side technologies in the electricity sector is regulated, which is not unilaterally supported (Joskow, 2012): "*But is this efficiency gain large enough to cover the additional costs of smart meters and associated information and automated distribution technology, both in the aggregate and for customers with different utilization characteristics?*" The answer to the question is different in the three markets considered, which helps in identifying the relevant institutional, economical, and technological determinants of the answer.

improvement. For example, retailers' bids in the market can incorporate information about the flexibility that resides at the household level. The focus is thus on how the wholesale market outcomes change with increased trade across hours, in contrast to the literature addressing the consumers' behavioral response to more information on the real-time prices (e.g. Allcott, 2011; Jessoe and Rapson, 2014).

[6] In the literature on information design, efficiency improvements can imply a greater deviation from the law of one price: Improved information can lead to prices more strongly associated with true seller quality and thus to prices that are more disperse (see, e.g., Hopenhayn and Saeedi, 2019). The impact on consumer welfare can depend on the convexity properties of supply (Schlee, 1996), but the mechanism for the result is different from ours.

2 Consumer welfare and missing trade: Analytics

Let $D(p)$ denote the consumer demand at price p, with $D'(p) \leq 0$. Consumer surplus is $W(p) = \int_{v \geqslant p} D(v)dv$, assumed to remain bounded.[7] Supply $S(p)$ is strictly increasing, $S'(p) > 0$. There is a finite price so that for all prices above that price $S(p) > D(p)$, and also $0 = S(0) < D(0)$: For some price p, we have $S(p) = D(p)$.

Frictions in goods trade can be micro-founded through an explicit inclusion of traditional trade costs (Samuelson, 1952) and information costs (e.g., Allen, 2014), resulting in "missing trade" and excess demand $x = D(p) - S(p)$ deviating from zero. As in Jensen (2007), it is useful to start by thinking of x as a supply shock: Fishermen out in the sea with catch and no communication technology may land randomly at distinct beach markets. The realization of x would then be a local supply shock that collapses to some $\overline{x}$ once communication is introduced; the catch can be traded out in the sea and then the local markets become integrated.[8] We take the localized excess demand shock x as given, with mean value $\overline{x}$ and cumulative distribution function $F(x)$ with domain M. This distribution generates a set of local market conditions, potentially a continuum.

We measure the expected consumer surplus before knowing the shock. The equilibrium price in any given state depends on realization x, $p = P(x)$. Think of all feasible excess demands as a function of price, $x = X(p) = D(p) - S(p)$, to observe that price function $p = P(x)$ inherits the convexity properties of the standard excess demand, $X(p)$.

The question is then: "Is the consumer better off with or without the friction-driven price dispersion?" The consumer surplus without the price dispersion is

$$W(P(\overline{x})) = W(\overline{x}) = \int_{v \geqslant P(\overline{x})} D(v)dv,$$

whereas under the dispersed prices the expected consumer surplus is

$$\mathbb{E}W(x) = \int_{x \in M} \int_{v \geqslant P(x)} D(v)dvdF(x).$$

Proposition 1 *Missing trade can benefit or hurt the consumer surplus. In particular:*

$$X''(p) < 0 \Rightarrow \mathbb{E}W(x) > W(\overline{x}).$$

[7] There exists some finite price so that for all prices above that price demand $D(p)$ has elasticity greater than unity, or one may assume that there is an upper bound for feasible prices that the consumer might face. The latter assumption is needed when the demand is inelastic.

[8] Jensen (2007) provides an explicit model of this situation with trade costs and information frictions.

Proof: Since F is a mean-preserving spread of $\overline{x}$, $\mathbb{E}W(x) > W(\overline{x})$ is equivalent to the strict convexity of $W(x)$. We have $W'(x) = -D(P(x))P'(x)$ and thus

$$W''(x) = -D'(P(x))P'(x)^2 - D(P(x))P''(x).$$

The first term in W'' is always positive. In the second term, $P''(x) < 0 \Leftrightarrow X''(p) < 0$. Hence, $W(x)$ is strictly convex if $X'' < 0$. Q.E.D.

Dispersed prices impact the consumer surplus in two ways. First, $W(p)$ is strictly convex in prices and thus an increased pure risk in prices benefits the consumer. Second, introducing pure risk to $\overline{x}$ not only adds the price risk but the level of prices changes as well. The concavity of the excess demand implies that the expectation of the dispersed prices falls below the sure price, $P(\overline{x})$. Taken together, the price dispersion and price level effects benefit the consumer, if $X''(p) < 0$.

Some cases are particularly useful:

Proposition 2 *In the above model of frictions it follows that:*

(i) *For inelastic demand,* $\mathbb{E}W(x) > W(\overline{x})$ *is equivalent to* $S''(p) > 0$*.*

(ii) *For inelastic supply,* $\mathbb{E}W(x) > W(\overline{x})$ *if* $D''(p) < 0$*.*

(iii) *If demand and supply are linear, then* $\mathbb{E}W(x) > W(\overline{x})$*.*

Proof: If $D'(p) = 0$, $W'' = -D(P(x))P''(x)$. Since $P''(x) < 0 \Leftrightarrow X''(p) < 0 \Leftrightarrow -S''(p) < 0$, it follows that the convexity of $W(x)$ is equivalent to the convexity of supply. For item (ii), $P''(x) < 0 \Leftrightarrow D''(p) < 0$, and so $D''(p) < 0 \Rightarrow W'' > 0$ but the reverse is not true. For item (iii), $D''(p) = 0 = S''(p)$, $W'' = -D'P''(x)^2 > 0$. Q.E.D.

The convexity of excess demand is the key to the welfare impact but careful attention should be paid to how it links to the source of the frictions. The model captures well the situation of supply shocks such as those in the fish market case. But the market conditions may vary also because the valuation of the good differs, for instance, between non-peak and peak demands for electricity. This impacts the welfare assessment, although the role of excess demand capturing the price level effect remains the same. Consider an inelastic demand $D + \tilde{x}$ where $\tilde{x}$ is a zero-mean demand shock. The locational market equilibria $D + \tilde{x} - S(p) = 0$ generate the consumer surplus outcomes,

$$W(\tilde{x}) = \int_{v \geqslant P(\tilde{x})} [D + \tilde{x}] dv,$$

with expected value $\mathbb{E}W(\tilde{x})$. Under frictionless trade, quantities are reallocated until prices converge,[9] and the integrated market can again be conceptualized through excess demand that sums realizations $D+\tilde{x}-S(p)$ at any given p over the markets. The resulting one price, $P(\overline{x})$, gives expected surplus $W(\overline{x})$ that dominates the surplus under no trade if the supply is convex in quantities (concave in prices): $S''(p)<0 \Rightarrow W(\overline{x}) > \mathbb{E}W(\tilde{x})$.[10] Intuitively, convexity means that trade reduces peak prices more than it increases the low prices. In contrast, if the supply is concave in quantities, the same line of reasoning shows that the price level is elevated by trade but yet the peak prices still decline. This can give a surplus gains to consumer if the peak consumption is relatively large.

In our application, separate locational markets are the hourly markets for electricity, and *shocks happen to both demand and supply.* For instance, intermittency of renewables can materialize as shifts in supply coming wind farms or as demand variation due to rooftop solar PV production. The quantification addresses the joint impact of both types of shocks and how the gradual scale-up of technologies reducing frictions will impact surpluses.[11]

3 Implementation

Approach

The data consists of a set of demand bids, $(p_i, Q_i)_{i\in\mathcal{D}_t}$, and a set of supply bids, $(p_j, Q_j)_{j\in\mathcal{S}_t}$, for any given market t (i.e., hour t of a day). If we collect from all bids $i\in\mathcal{D}_t$ and $j\in\mathcal{S}_t$

[9]Direct trade of utils is not needed if traders can ship production from low demand markets to high demand markets.

[10]Term $W(\tilde{x})$ gives $W'(\tilde{x}) = -[D+\tilde{x}]P'(\tilde{x}) + \int_{v\geqslant P(\tilde{x})} dv$, and $W''(\tilde{x}) = -2P'(\tilde{x}) - [D+\tilde{x}]P''(\tilde{x})$. Since $P''(\tilde{x})>0$ is equivalent to $S''(p)<0$, it follows $W''(\tilde{x})<0$ if the supply is convex.

[11]The literature on real-time pricing of electricity brings in important issues specific to electricity. Borenstein and Holland (2005) control for the share of price responsive consumers, and focus on long-run outcomes where capacities respond to the price level changes. Whereas the long-run capacity cost is linear, the short-run cost is strictly convex in their assessment of welfare impacts. Real-time pricing reduces the total capacity, and, fundamentally, the result follows since the expected (short-term) price level declines as the price dispersion shrinks, consistent with us. Ambec and Crampes (2019) also note that exposing consumers to price volatility can increase the consumer surplus.

those that are activated at some given price p, we obtain

$$\hat{\mathcal{D}}_t(p) = \{i : p_i \geq p\}$$
$$\hat{\mathcal{S}}_t(p) = \{j : p_j \leq p\},$$

and, then with these, we can define an excess demand for an hour:

$$x_t = X_t(p) = \sum_{i \in \hat{\mathcal{D}}_t(p)} Q_i - \sum_{j \in \hat{\mathcal{S}}_t(p)} Q_j.$$

In each hour, the actual market equilibria reported by power exchanges satisfies $x_t = 0$. However, we do not have access to the precise routines operated by the exchanges, and therefore we seek to replicate these routines by using a formal model to interpret how the set of activated bids is achieved from the universe of bids in actuality. The model takes the bids as data and implements the following linear program for the total surplus maximization hour-by-hour:

$$\begin{aligned} \max_{d_i, s_j} \sum_{i \in \mathcal{D}_t} p_i d_i - \sum_{j \in \mathcal{S}_t} p_j s_j \qquad (1) \\ \text{s.t.} \quad d_t =& \sum_i d_i, \quad 0 \leq d_i \leq Q_i,\ i \in \mathcal{D}_t \\ s_t =& \sum_j s_j, \quad 0 \leq s_j \leq Q_j,\ j \in \mathcal{S}_t, \\ x_t =& d_t - s_t = 0. \end{aligned}$$

where d_i and s_j are the quantities of bids that are activated, and d_t and s_t are the sum of the activated demand and supply bids over the hour. The market price is the shadow price of the constraint that supply equals demand; at that point, the marginal value of increasing demand matches the marginal value of decreasing supply.[12] Note that market power and other inefficiencies that may exist in the bid data are not addressed in any way: Bids come as they are, and the program finds the equilibrium allocation that is efficient given those bids.

We turn next to the second model that we use for producing the counterfactuals. Model (1) finds hourly prices so that $x_t = 0$ separately for each hour of the day, $t \in \mathcal{T}$, whereas model (2) below does the same by aggregating over hours of the day:

[12] A uniform price auction can be efficiently solved through a linear program, an idea dating back to Samuelson (1952). The approach is the basis of market price calculation in power exchanges (see e.g. Hogan, 2014).

$\sum_{t\in\mathcal{T}} x_t = 0$. Thus, instead of considering welfare hour by hour, we extend to a simultaneous evaluation of the welfare in all hours of the day:

$$\max_{d_i, s_j} \sum_{t\in\mathcal{T}} \left[\sum_{i\in\mathcal{D}_t} p_i d_i - \sum_{j\in\mathcal{S}_t} p_j s_j \right], \tag{2}$$

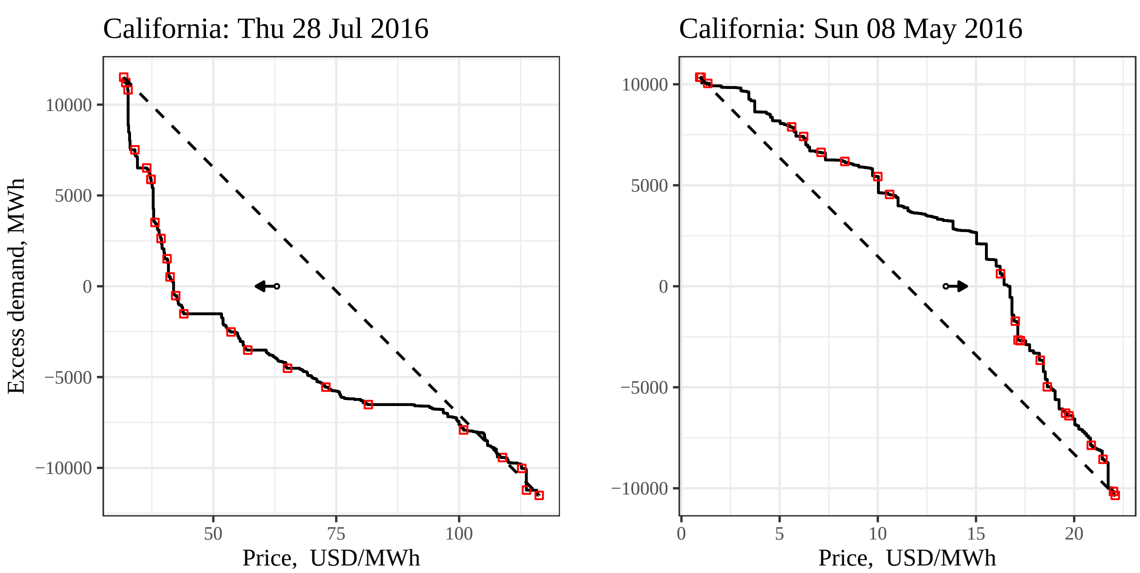
where we relax the hourly supply–demand balance constraints with a possibility to "trade" a net quantity y between the hours:

$$d_t - s_t = x_t, \quad \forall t,$$
$$-y \le x_t \le y, \quad \forall t,$$
$$\sum_{t\in\mathcal{T}} x_t = 0.$$

Here y gives the maximum capacity, that is, how many units can be reallocated from or to any given hour.

To illustrate Models (1)-(2) in action, Fig. 2 offers a view on daily excess demands in two days in California, using data that is introduced just below. The vertical axis gives the realization of the excess demand and the horizontal axis depicts the price. With no trade across hours, each hour $t = 1, .., 24$ is a single point on the curve. The expected price over the hours is to the right (left) of the curve if the curve exhibits

Figure 2: Excess demand curves in data



Notes: Red dots represent the actual hourly prices in California in two days. The curve in each figure represents the daily excess demand for one GW capacity for trade across hours. The circle is the consumption-weighted expected price without trade, and the arrow indicates the move of the expected price due to trade across hours.

convexity (concavity), denoted by a circle in each panel.[13] Trade across hours can be visioned as a process that takes quantities from the highest price hour until this price meets the second price, with the associated quantity given by the graph, and so on. With unlimited capacity for reallocations, the prices collapse to a single daily price. With the trade capacity limited to 1 GW, the prices become more compressed but yet some price dispersion remains (not depicted). The change in the expected price, obtained from the compressed prices, is denoted by the arrow in each panel. On the left panel, the expected price declines but, on the right, the trade increases the price.

Institutions and data

Table 1 provides a snapshot of the common characteristics of the electricity markets in California, the Nordics, and Spain. In all markets the deployment of renewable electricity supply is well under way but there is variation in the share of flexible energy sources (hydro) that provide counterbalance for the intermittent power (solar and wind). Our focus is on the wholesale markets where the areas have sufficient similarity in the institutional arrangements and volumes of trade are by an order of magnitude larger than in real-time markets. The final retail tariffs paid by consumers include taxes, levies, and grid charges, and the retailer's margin. Yet, the analysis of wholesale prices detects the changes in surplus, assuming that the other factors remain constant.

Table 1: Summary statistics

		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
Wholesale market price	c/kWh	3.76	2.94	5.22
Residential electricity tariff	c/kWh	19.65	20.85	23.83
Number of households	million	14.7	11.8	18.3

Notes: Summary statistics for the markets in 2017. Sources: EIA, EuroStat.

[13]The expectation is the consumption-weighted average price.

We have gathered a data set of over 140 million bids from the operators of the three markets, CAISO (California), Nord Pool (Nordic), and OMIE (Spanish/Iberian), from period 2011–2018. Each bid in our final data set is a price-quantity pair for one hour in the day-ahead market, with typically a few thousand bids by hour in each area.

The markets differ in their approach to technicalities, including how: the real-time power system operation is connected to the day-ahead market; some of the actual bids can be submitted in a more complex manner than as simple price–quantity pairs; and the location of bid resource and related transmission constraints in the power system are taken into account in the market clearing. For example, in California, there are in principle 3,000 locational markets.

We consolidate the raw data from the operators into one coherent data set by the following preprocessing steps. First, we use ancillary market data to exclude from the bids any resources that are committed to serve the real-time markets. Second, we deconstruct the complex bid structures, which for example allow firms to express their ramping up and down costs more explicitly, to single bids; that is, these are reduced to price–quantity pairs for each hour separately. Third, we construct for each market a "system equilibrium", i.e. equilibrium price–quantity outcome that would emerge if all transactions within the market area were physically implementable without any transmission constraints. The system equilibrium is conceptually well defined, i.e. it exists for all markets, although such an equilibrium is explicitly reported only for the Nordics.

We test the match between the model output and actual equilibrium prices. In the Nordics, the model maps the preprocessed bids to actual market outcomes precisely: 99% of the modelled equilibrium prices are within €.51/MWh of the reported system prices; on average, the gap between the two prices is €.05/MWh. The mean of the locational prices in Spain differs by €.34/MWh from our model predictions, and in California the model price on average falls short of the mean of the locational prices by $3.1/MWh. These findings are as expected: The Nordic data is exactly on the system equilibrium that our model seeks to replicate; the Spanish zonal system comes close to the full system equilibrium; and the nodal price data in California implies a greatest deviation from the system outcome.[14]

[14] Online Appendix A provides the detailed preprocessing steps and also quantitative analysis of the model performance in each market. The Data Set contains the codes for the replication of the steps.

4 Results

Consumer surplus

Figure 3 reports the change in consumer surpluses day-by-day and the cumulative sum of the daily values in California, the Nordic market, and Spain over the year 2016. The results shown are for 1 GW capacity for reallocating quantities from or to any given hour; the change in surplus is in comparison to no-trade outcomes. The surplus measure is the traditional consumer surplus, obtained from the demand curve defined by the actual demand bids. The three markets offer notably different surpluses over the year.

In California, the differences between the hourly prices within a day start to increase in the spring, with depressed day prices and peaking evening prices. The solar PV systems crowd out the traditional mix of gas-fired generation when the sun rises but the gas-fired units must quickly ramp up when the sun sets.[15] In such a situation, trade across hours works against the consumers as trading that reduces the price dispersion also increases the daily price level. The demand is relatively inelastic and varying, and the supply comes from the concave part of the supply curve (see Video, Panel A). The trade raises the low prices more than it reduces the peak prices. As a result, consumers lose day-by-day, until the trend is reversed later in the summer. Higher demand for cooling pushes the power system closer to full capacity and the trade across hours starts to work in the convex part of the supply curve (see Video, Panel B). Trade away from the high price hours leads to the reduction of peak power generation and lowers the peak prices quicker than the prices rise during the off-peak periods. In the end, over the year, the consumer barely breaks even in Fig. 3.

In the Nordic market, the daily price dispersion remains small for a large part of the year, as the hydro resource provides enough flexibility to counterbalance wind power intermittency and demand variation. Nearly all of the consumer welfare gain for the full year 2016 comes from a few winter days when a cold spell leads to peaks in electric heating demand and prices. The demand is inelastic and varying, and the supply is convex (see Video, Panel C). The trade reduces the bite of the market-level capacity constraint in production and delivers consumer surplus gains that are by multiple factors larger than in the other markets in this comparison.

In Spain, the bid data suggest that demand is more elastic than in the other markets,

[15] See Borenstein and Bushnell (2015) for a discussion of the phenomenon.

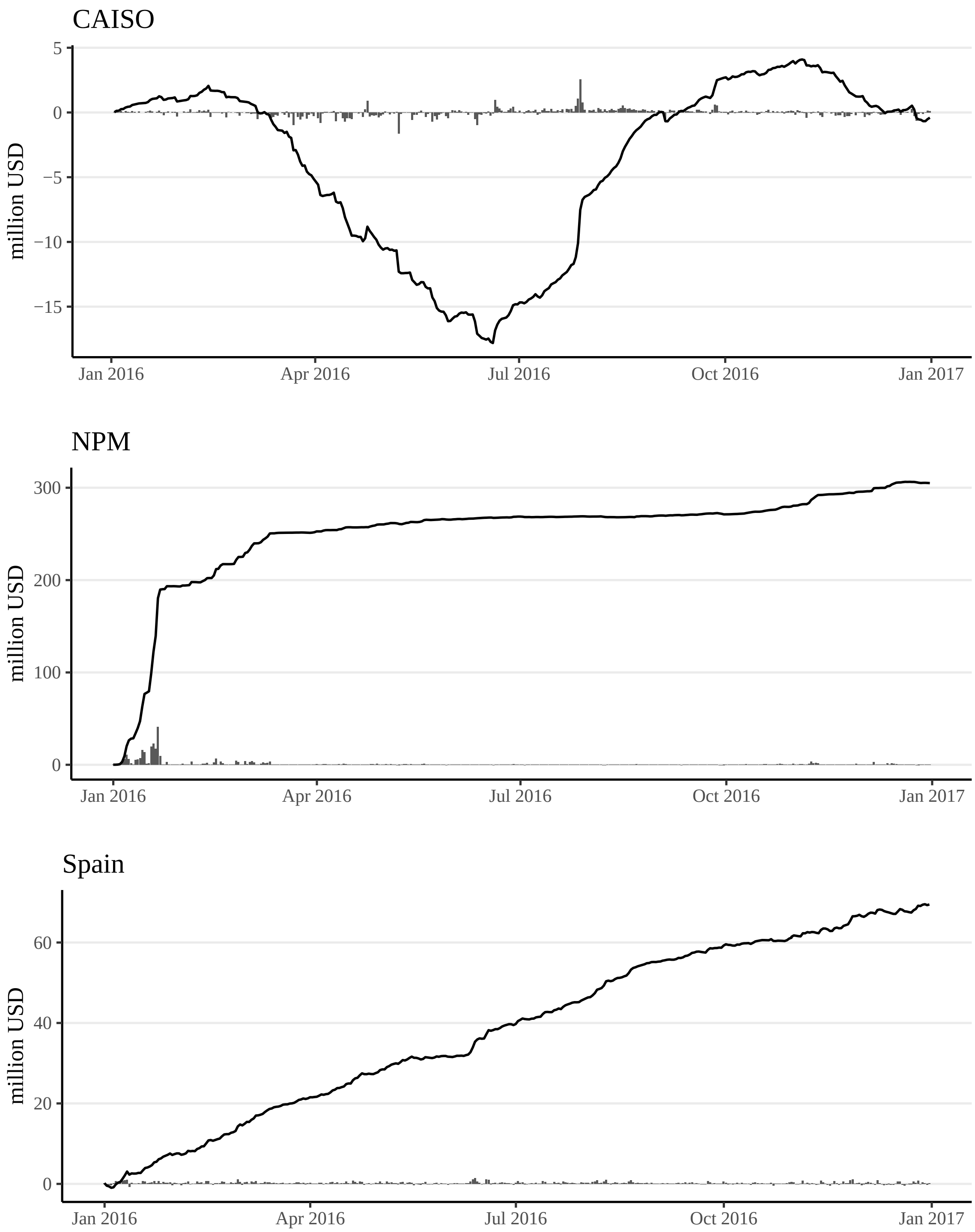
bringing stability to the surplus gain over the course of the year: The demand elasticity reduces the price peaks and prevents prices from dwindling quickly. A marked convexity or concavity of the excess demand is missing in Spain, consistent with demand and supply being closer to linear (see Video, Panel D).

The exercise just presented for 2016 is repeated for all three markets and each of the years in 2011–2018, subject to data availability, in Table 2. In California we lack a longer history, but can note that the change in consumer surplus has increased from 2015 to 2018. A more detailed look reveals that it is the peak prices during the summer, not unlike the peaks in the Nordic winter, that contribute to the increases in consumer surplus. The longer time horizon in the Nordic market reveals large variations in the consumer surplus, from -19 million euro in 2011 to 465 million euro in the following year. The availability of the key hydro resource offers a narrative supportive of the results: In early 2011 hydro reservoirs were overfull, leading to a similar phenomenon as in California where the solar PV "overproduction" causes the demand to meet supply in the concave part of the supply curve. Trade across hours increases the lowest prices more than it reduces highest prices, so the average prices increase. In 2012, drier and colder weather reverses the impact on consumers, following reasoning just explained for 2016. In Spain, the annual consumer surplus gain has had a persistent downward trend over the past few years. Such changes are consistent with increased demand elasticity that is to some extent even visually detectable in the bid data. It should be borne in mind that our counterfactual analysis adds flexibility to whatever is already in the bid data: A trend in demand elasticity embodied in the bids crowds out the impact that our efficiency-improving experiment can have.

Welfare

Table 2 reports also the change in welfare. The welfare measure is otherwise as defined by the textbook consumer and producer surpluses, obtained from the bid curves, but one must add the social value of the technology for trading, that is, the gain obtained by efficiently allocating the trade capacity to exploit the price spreads across hours. The total welfare gains generated by trade are less than 1% of the total wholesale market value in all areas and in all years. Changes in consumer surpluses are mirror images of the changes in producer surpluses, and the overall allocative improvements are modest. One explanation for this is that the total quantities do not change markedly over a

Figure 3: Change in consumer surplus



Notes: Changes in consumer surpluses in California (top panel), the Nordic market (middle) and Spain (bottom). The comparison is between the counterfactual equilibrium with 1 GW trade and the equilibrium without trade. Each bar on the horizontal axis represents the change in surplus over one day (calculated as a sum of the hourly values) and the lines show the cumulative sum of the daily values in 2016.

Table 2: Changes in consumer surplus and welfare

	California		Nordic		Spain	
	Consumer surplus gain	Welfare gain	Consumer surplus gain	Welfare gain	Consumer surplus gain	Welfare gain
2011			-19	17	150	34
2012			465	19	188	46
2013			176	16	194	53
2014			85	14	118	47
2015	*26*	*16*	147	14	88	42
2016	−0.4	26	305	16	69	30
2017	202	63	145	12	64	33
2018	210	84	260	20	20	31

Notes: Changes in consumer surplus and welfare as a result of recalculated day-ahead market equilibria when an increase of 1 GW (around 1 million households) of price responsive flexible technology is included in the market price calculation. Values reported in million U.S. dollars or euro. Data for California from March 2015–.

trading cycle – if the demands were totally inelastic, there would be no change at all in the daily quantities[16]. The efficiency gains from reshuffling a given total quantity within a day remain limited. On reflection, the lack of allocative gains is not surprising, as electricity markets are not nascent and the market participants have a variety of existing technologies for materializing efficiency improvements.[17]

The approach also gives us a breakdown of how the welfare gain is divided between the traders (those holding the trade capacity), consumers, and producers. With 1 GW capacity, traders capture the largest share of the efficiency gain, on average 87% in California, 71% in the Nordic market and 81% in Spain over our time period. This translates to annual arbitrage gain of $41 million in California, €11 million in the Nordic market and €32 million in Spain. As a very rough point of comparison, the 1 GW quantification corresponds to 1 million households with new technologies adjusting their demand in response to market prices. Using such a simple arithmetic, the annual gains per household range from €11 in the Nordic area to €32 in Spain and $41 in California.

[16]In the 1 GW experiment, the changes of daily quantities are between -1.0% – 0.6% in California, -0.7% – 0.5% in the Nordic market, and -2.2% – 1.2% in Spain. Indeed, it is the mean price level changes that explain most of the change in consumer surplus; see Online Appendix B.1.

[17]These include: flexible power plants, industrial storage units, and industrial demand response.

These private gains can be contrasted against the cost of installing a smart meter, roughly \$200 per device installed *en masse*, and the added cost of flexible technologies, such as a smarter air conditioner, heat pump or thermostat; or the cost of supplying the flexibility from industrial sources.

It may be surprising that the average annual change in consumer surplus is largest in the Nordics but the welfare gain (including arbitrage gain) is the smallest. The result is explained by the steeply convex supply curve and inelastic demand in the Nordic market: A small increase in trade across hours leaves the total quantities almost unchanged but yet results in a large decline in the price level. The larger gain to the arbitrage traders in California is a consequence of equilibrium prices being less sensitive to the increased trading across hours.

Robustness

The results come with a few immediate caveats that should not affect the result that there are structural differences between the markets but may affect the quantitative results. For an extensive scale-up of trade, the bids that we take as data are likely to change as well. The smaller is the capacity for trading across hours, the more trust can be placed on the results. We run robustness checks by varying the trade capacity. For instance, the impact on consumer welfare follows a very similar reasoning for trade capacity that is by factor 10 smaller, or by factor 3 bigger. Bearing in mind the caveat on bids, one can also quantify the size of the trade capacity that generates the largest surplus to the owners of the capacity. This is one gauge of the money on the table for the new technologies. Our quantification set this maximum gain at a surprisingly modest level: \$128 million in California (in 2018), €15 million in Nordics (in 2018), €63 million in Spain (2013).[18] Again, these maximum gains are markedly different across the three markets.

5 Concluding remarks

Do consumers gain when new technologies improve the efficiency of goods trade? The answer is much less obvious than what one may infer from the extensive evidence on the benefits of technologies reducing information and other trade frictions. Understanding surplus impacts is important both for private and public policies. If, for instance, better

[18] Online Appendix B.2 and B.3 provide the detail.

trading technologies increase the producer side surplus through higher average prices, investments in production capacity are encouraged. Thus, the two technologies are complements, while the case for substitutes arises when the consumer surplus increases. As also noted by Borenstein and Holland (2005), short-run surplus changes shape the long-run investments to the market, which is particularly important if information technologies used for trading are regulated or subsidized.

As new technologies improve price-responsiveness, they may limit market power (Joskow and Tirole, 2007), and thus they have implications for policies on competition and information technologies. Our result that increasing trade by better technologies can cause a sizeable shift of surplus from producers to consumers can also be read in the other direction: strategically avoiding the use of such technologies can shift surplus to producers.

References

Aker, Jenny C. 2010. "Information from Markets Near and Far: Mobile Phones and Agricultural Markets in Niger." *American Economic Journal: Applied Economics*, 2(3): 46–59.

Allcott, Hunt. 2011. "Rethinking real-time electricity pricing." *Resource and Energy Economics*, 33(4): 820–842. Special section: Sustainable Resource Use and Economic Dynamics.

Allen, Treb. 2014. "Information Frictions in Trade." *Econometrica*, 82(6): 2041–2083.

Ambec, Stefan, and Claude Crampes. 2019. "Decarbonizing electricity generation with intermittent sources of energy." *Journal of the Association of Environmental and Resource Economists*, 6(6): 1105–1134.

Borenstein, Severin, and James Bushnell. 2015. "The US Electricity Industry After 20 Years of Restructuring." *Annual Review of Economics*, 7: 437–463.

Borenstein, Severin, and Stephen P. Holland. 2005. "On the Efficiency of Competitive Electricity Markets With Time-Invariant Retail Prices." *RAND Journal of Economics*, 36(3): 469–493.

Borenstein, Severin, James Bushnell, and Frank A. Wolak. 2002. "Measuring Market Inefficiencies in California's Restructured Wholesale Electricity Market." *American Economic Review*, 92: 1376–1405.

Bulow, Jeremy, and Paul Klemperer. 2012. "Regulated Prices, Rent Seeking, and Consumer Surplus." *Journal of Political Economy*, 120(1): 160–186.

Bushnell, James, Erin Mansur, and Celeste Saravia. 2008. "Vertical Arrangements, Market Structure and Competition: An analysis of Restructured U.S. Electricity Markets." *American Economic Review*, 98: 237–266.

Fabra, Natalia, and Mar Reguant. 2014. "Pass-Through of Emissions Costs in Electricity Markets." *American Economic Review*, 104(9): 2872–2899.

Hogan, William W. 2014. "Electricity Market Design and Efficient Pricing: Applications for New England and Beyond." *The Electricity Journal*, 27(7): 23–49.

Hopenhayn, Hugo, and Maryam Saeedi. 2019. "Optimal Quality Ratings and Market Outcomes." NBER Working Paper 26221.

Hortaçsu, Ali, and Steven Puller. 2008. "Understanding Strategic Models of Bidding in Deregulated Electricity Markets: A Case Study of ERCOT." *RAND Journal of Economics*, 39(1): 86–114.

Ito, Koichiro, and Mar Reguant. 2016. "Sequential Markets, Market Power, and Arbitrage." *American Economic Review*, 106(7): 1921–57.

Jensen, Robert. 2007. "The Digital Provide: Information (Technology), Market Performance, and Welfare in the South Indian Fisheries Sector*." *The Quarterly Journal of Economics*, 122(3): 879–924.

Jessoe, Katrina, and David Rapson. 2014. "Knowledge Is (Less) Power: Experimental Evidence from Residential Energy Use." *American Economic Review*, 104(4): 1417–38.

Joskow, Paul L. 2012. "Creating a Smarter U.S. Electricity Grid." *Journal of Economic Perspectives*, 26(1): 29–48.

Joskow, Paul L., and Catherine D. Wolfram. 2012. "Dynamic Pricing of Electricity." *American Economic Review*, 102(3): 381–85.

Joskow, Paul L., and Jean Tirole. 2007. "Reliability and competitive electricity markets." *The RAND Journal of Economics*, 38(1): 60–84.

Lawrence Berkeley National Laboratory. 2017. "2025 California Demand Response Potential Study." Technical report.

Newbery, David, and Joseph Stiglitz. 1979. "The Theory of Commodity Price Stabilisation Rules: Welfare Impacts and Supply Responses." *The Economic Journal*, 89: 799–817.

Reguant, Mar. 2014. "Complementary Bidding Mechanisms and Startup Costs in Electricity Markets." *Review of Economic Studies*, 81(4): 1708–1742.

Samuelson, Paul A. 1952. "Spatial Price Equilibrium and Linear Programming." *American Economic Review*, 42(3): 283–303.

Schlee, Edward E. 1996. "The Value of Information about Product Quality." *The RAND Journal of Economics*, 27(4): 803–815.

Steinwender, Claudia. 2018. "Real Effects of Information Frictions: When the States and the Kingdom Became United." *American Economic Review*, 108(3): 657–696.

Turnovsky, Stephen J., Haim Shalit, and Andrew Schmitz. 1980. "Consumer's Surplus, Price Instability, and Consumer Welfare." *Econometrica*, 48(1): 135–152.

Waugh, Frederick V. 1944. "Does the Consumer Benefit from Price Instability?" *The Quarterly Journal of Economics*, 58(4): 602–614.

Wright, Brian. 2001. "Chapter 14 Storage and price stabilization." In *Marketing, Distribution and Consumers*. Vol. 1 of *Handbook of Agricultural Economics*, 817–861. Elsevier.