Redistribution through technology: Equilibrium impacts of mandated efficiency in three electricity markets

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January 2, 2023

Abstract

We consolidate, generalize, and expand on a set of price theory results to measure consumer benefits from technologies that improve the efficiency of allocations in markets. We then conduct the same efficiency-improving experiment in three major electricity markets. The convexity of excess demand, obtained from the bids to buy and sell, is a novel measure that strongly predicts consumer benefits in all markets. It highlights that small allocative improvements from technology mandates lead to large redistributions of surplus benefitting consumers.

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

Keywords: Information technology, frictions, trade, electricity

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1 Introduction

New technologies offer captivating opportunities to trade and improve efficiency in markets, illustrations ranging from mobile phones (e.g., Jensen, 2007) to smart technologies for electricity consumption (e.g., Jessoe and Rapson, 2014). Aware of this, policy makers have sought to harness these opportunities in electricity markets by mandating the adoption of smart consumer technologies and new producer technologies such as large-scale storage. The mandates have broad equilibrium impacts when the market adoption of technologies is not otherwise taking place. On account of equilibrium impacts, do consumers end up benefitting from the mandated allocative efficiency?

Theoretically, the answer turns out to be non-trivial. First, the mandates have an impact on equilibrium price dispersion and thereby on one source of surplus to consumers. Intuitively, a consumer benefits from the option to optimize, e.g., to charge an electric vehicle at occasional bargain prices rather than at a flat mean-equivalent price.[1] A market-level improvement in efficiency reduces price dispersion and thus those consumers who can respond to price variations lose gains from the option to do so. The importance of this option can be captured by a pass-through rate measuring the incidence of allocative inefficiency between consumers and producers.[2] Second, if supplies are positively correlated with demands, consumers can get frequent bargain prices even when they do not respond to prices at all. The mandated efficiency makes such bargains smaller. Third, the mandates change the overall price level that consumers face. We develop a novel measure predicting this change: it measures the convexity of market excess demand. Under convexity (concavity), an improved allocative efficiency contributes positively (negatively) to the consumer surplus. The convexity measure links the consumer surplus gains to the market rudiments, the shapes of demand and supply.[3]

[1]This result follows from elementary microeconomics when preferences 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 more generally, under certain restrictions on preferences (Turnovsky, Shalit and Schmitz, 1980).

[2]This use of the concept can be added to the long list of its applications. The pass-through rate typically measures how firms pass cost shocks to prices (e.g., Weyl and Fabinger, 2013), with applications in taxation, oligopoly (e.g., Genagos and Pagliero, 2021), monopolistic competition (Mrázová and Neary, 2014 or Mrázová and Neary, 2017), international trade (De Loecker and Goldberg, 2014), and, e.g., in the energy sector (Fabra and Reguant, 2014).

[3]In contrast to the convexity of profit function or concavity of expenditure function, the convexity of excess demand is not an implication of the theory but rather a primitive linking to the distributions

We obtain these results using a simple price-theory model that consolidates, generalizes, and expands on a set of scattered results in the literature. We then develop empirical counterparts of the pass-through rate, correlation, and the convexity of excess demand by using a micro-data on over 160 million bids from three distinct markets trading identical goods: the electricity wholesale markets in California, Nordic countries, and Spain. This enables us to conduct the same efficiency-improving "mandate" in each market to quantify the three determinants of surplus variations. In the experiment, we use the actual bids for market clearing after adding 1 gigawatt (GW) of capacity for improving the efficiency of allocations, hour by hour.[4] Whether it is a retailer controlling customers' consumptions taking advantage of smart meters and remote controls, a producer exploiting grid-based storage solutions, or an individual optimizing the charging of EV, the idea is to buy market electricity when prices are low and sell (or, not use) it when prices are high.

A consistent result arises from all three markets: the private trading surplus may be lost with a reduced price dispersion but the consumer benefit from a lower price level is overwhelming. This price-level effect is captured by the empirical convexity measure of excess demand. It explains close to 90% of the surplus variation for California, 80% for the Nordics, and 40% for Spain. Price level changes have a flip-side implication: incumbent firms end up losing surplus in all markets; the surplus redistribution is substantially larger than the social value of the technologies which is low in all markets.

The excess demand, the difference between the demand and the supply, inherits its convexity properties mainly from the supply if the demand is relatively inelastic. In Fig. 1, the mean hourly supply curve for electricity in California shows a concave-convex pattern:[5] in our data from 2015-2020, according to Jensen's inequality, the excess demand is convex in 67% of the hours. This convexity associates closely to a supply taking a convex form in quantities; in the Nordics and Spain the shares are 52% and 46%, respectively. This variation matters: consumers tend to benefit (lose) from an efficiency mandate when the supply is convex (concave) in quantities. Intuitively, a

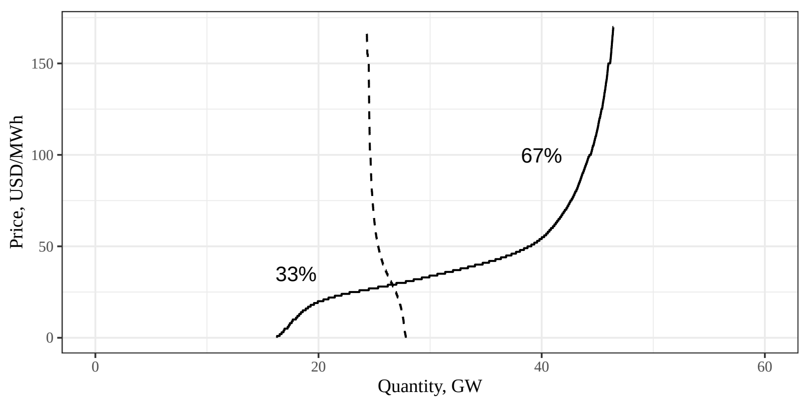
of costs and valuations. Its relevance for price level changes from trade has been acknowledged in the literature on price stabilization (Just et al., 1978).

[4]This quantity is roughly equal to the demand response coming from one million households; see, for example, Lawrence Berkeley National Laboratory (2017).

[5]It is natural to think that concavity/convexity is w.r.t. the variable on the horizontal axis, and this is what we assume in this discussion. In the formal analysis, we follow the conventions and assume that the demand and supply are functions of the price.

steeply rising supply reservation price of a convex supply reflects a shortage, an "under-supply" situation in which a technology such as a large-scale storage helps in lowering the average price. In contrast, the same technology increases the average price when the supply is concave, an "over-supply" situation in which there is a large supply (e.g., gas-fired power) coming available when the price exceeds a certain reservation level. By Jensen's inequality, an efficiency mandate thus either reduces or increases the mean price depending on if there is under- or over-supply, both situations being frequent in these markets with high shares of intermittent renewables.

Figure 1: Average supply and demand curves in California, 2015-2020



Notes: The mean of the hourly supply and demand in California, 2015-2020. 33% (67%) is the share of equilibria in which the convexity measure indicates a concave (convex) supply.

We estimate that when the mandate changes the daily price expectation by one euro/dollar, the daily consumer surplus changes by .226 million in California, 1.06 million in the Nordics, and .147 million in Spain. The mandate can change the price expectation in either direction, depending on the variation of under- and over-supply situations, and therefore the final impact of the mandate on consumer surpluses accumulates as a function of this variation in days over a year. For 2015-2020, we evaluate that the mandate of controlled size $1GW$ would have benefitted consumers in all markets. In the Nordics, the surplus gain to consumers from a mandate of size $1GW$ is ten times larger than the total (gross) social surplus!

The results from micro-data concur with the simulation results in Butters, Dorsey and Gowrisankaran (2021) who also find that the mandates in California generate a low gross surplus in total.[6] Strikingly, they find that the policy mandate of installing ca. $5GW$ of storage would be reached as an efficient market outcome as late as 2044.

[6] Karaduman (2021) has a related focus with data from South Australia.

California requires that utilities procure 1.3GW of storage power capacity by 2024; at least seven US states have targets for storage capacity. We develop a storage-model to map our generic mandate of 1GW into the actual storage needed for the same effect: this analysis shows that the generic 1GW mandate corresponds closely to the mandate in California for 2024. In the Nordic market, the generic mandate of 1GW translates into a larger storage power capacity, but the main conclusions remain: the mandates imply large redistributions of surplus but generate low social values in total. These results follow because under-supply situations, in which consumers benefit from the mandates, dominate the evaluation in the data period. However, the conceptual observation leads to a more general conclusion: in the over-supply situations, with a concave supply, the implications for the consumer surplus are reversed. The concave part of the supply likely becomes increasingly relevant when the share of renewables scales in the near future.[7]

In addition to storage, the results apply to any policy that manages to implement the assumed improvement in the efficiency of allocations. It could, in principle, result from a large-scale program exposing households to real-time pricing such as the one introduced by Spain in 2015 (Fabra et al., 2021).[8] There is a literature on how to activate consumers to use ever better smart appliances and associated control mechanisms for responding to price variations (e.g., Allcott, 2011; Jessoe and Rapson, 2014; Fabra et al., 2021; Ito, Ida and Tanaka, 2021; Fowlie et al., 2021). The final surplus from the technologies will be produced by the market, and therefore a first-order question, not addressed by this literature, is how a large-scale deployment of consumer-side technologies impacts the market equilibrium. Clearly, the demand-side surplus of the wholesale market is not directly the final end-user surplus but it is the root of the gains: how quickly the price impact trickles down depends, e.g., on the organization of retail pricing. There are important differences between the markets in this respect.

The multi-market approach may prove useful when studying, for example, the impact of data centers and cryptocurrency mining on the "world electricity market". For such questions, it seems necessary to make apples-to-apples comparisons by transforming bids

[7] By determining directly from the bids how a given capacity portfolio generates surpluses and what the effect of a marginal investment is, our results provide information that seems relevant for planners who decide on capacity expansions. The capacity portfolio is often determined by capacity mechanisms instead of purely market-based investments (Joskow, 2019; Grubb and Newbery, 2018; Wolak, 2021*b*,*a*).

[8] EU directives 2009/72/EC and 2012/27/EU explicitly target improvements in market efficiency. Wolak (2019) discusses the general motivations for the policies.

in different power systems into comparable objects. We offer one approach to making headway in this comparison.[9]

Finally, this paper contributes to the literature on the impact of new technologies on market efficiency (e.g., Jensen, 2007; Aker, 2010; Allen, 2014; Steinwender, 2018). The impact on price dispersion and efficiency has been well documented, but the literature says little about the incidence of impacts. For instance, in Jensen (2007) the adoption of mobile phones reduces the dispersion of prices, which eliminates occasional bargain prices, but yet, according his empirical results, consumers end up gaining surplus. Our theory is broad enough to shed light on the possible mechanisms in such situations. We believe this paper is the first-ever study using a measure of excess demand, a rudimentary concept in economics, in empirical analysis.[10]

2 Consumer surplus and efficiency: Analytics

Abstract first from any particular market interpretation and let i be a "local" market in a set of markets $\mathcal{I}$. In each $i \in \mathcal{I}$, there is demand $D_i(p)$ and supply $S_i(p)$ depending on price p. The local markets differ because of location-specific demand and supply shocks d_i and s_i,

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

Each market thus shares a common demand primitive $D(p)$, assumed to be decreasing $D'(p) < 0$, and a supply primitive $S(p)$, assumed to be increasing $S'(p) > 0$. The local excess demand $X_i(p)$ is strictly decreasing, $X_i'(p) < 0$, and we assume that there is in each locality a finite price $p_i > 0$ such that $X_i(p_i) = 0$ for all $i \in \mathcal{I}$.

Consider then efficient trade between the local markets: for some price $p > 0$, it holds that $\sum_{i\in\mathcal{I}} X_i(p) = 0$. The aggregate excess demand is strictly decreasing and we assume

[9] The literature on electricity concentrates on single market settings, with a few exceptions. Callaway, Fowlie and McCormick (2018) look at different US markets in a simulation study focusing on the location-specific impacts of renewable on the electricity systems. Similarly Abrell, Rausch and Streitberger (2019) study the differences across locations in Europe.

[10] There is a large literature on the welfare impacts of price stabilization; see Wright (2001) for an overview and, e.g., Newbery and Stiglitz (1979). The literature on the energy transition has noted the need to develop measures of the consumer welfare. Ambec and Crampes (2021) study the welfare impact of volatility in a theory model where consumers are risk averse; see also Helm and Mier (2021).

that there is a positive price at which it vanishes. In the efficient outcome the demand and supply primitives satisfy $D(p)-S(p)=\overline{x}$, with $\overline{x}$ being the mean of the local market conditions $x_i \equiv s_i - d_i$. Intuitively, the efficient trade neutralizes the impacts of shocks across the markets.

Drop i and take $x=s-d$ as the local market condition, with cumulative distribution function $F(x)$ on domain M. Thus, $\overline{x}$ corresponds to the efficient trade, and the localized outcomes are associated to a mean-preserving spread of $\overline{x}$ given by F. We assume that "technology" determines which outcome holds. For instance, the realizations of x could capture local supply shocks that collapse to $\overline{x}$ once a communication technology allows trading across locations.[11] In electricity markets, the local markets are typically hourly markets in a day, with both components of $x=s-d$ varying across hours, due to, e.g., intermittent supplies and temperatures affecting demands.[12] The technology captures anything that enables the move from the local to the efficient trade.[13]

We impose a Gaussian structure on F through the following assumptions on s and d,

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

where σ_s and σ_d are standard deviations, and r is the correlation coefficient. Since d and x are jointly normally distributed,

$$\begin{aligned} \mathbb{E}(d|x) &= \mathbb{E}(d) + \frac{Cov(d,x)}{Var(x)}(x-\mathbb{E}(x)) \\ &= \frac{Cov(d,x)}{Var(x)}x \\ &= ax \qquad\qquad \text{with} \qquad a \equiv \frac{r\sigma_s\sigma_d - \sigma_d^2}{\sigma_s^2+\sigma_d^2-2r\sigma_s\sigma_d}. \end{aligned}$$

A local shock x is a pure supply shock if $\sigma_s>0$ and $\sigma_d=0$, and it is a pure demand shock if $\sigma_s=0$ and $\sigma_d>0$. More generally, x increases the demand expectation, $a>0$, if and only if the demand and supply are positively correlated such that $r>\sigma_d/\sigma_s$.

[11] Jensen (2007) considers fishermen landing in physically separate beach markets. The communication technology allows trading the catch out in the sea before the landings.

[12] In addition, physical locality of supply and demand can be an important characteristic of electricity markets (see, e.g., Graf and Wolak, 2022).

[13] The focus on the two extreme cases is inconsequential in this analytical model, and the efficiency impact of a technology will be partial in our empirical model. The empirical model lends itself to the analysis of specific technologies.

The consumer does not know the price in advance but will known it before the consumption choice is made, giving the expected surplus

$$\mathbb{E}W = \int_{x\in\mathbb{R}} \int_{d\in\mathbb{R}} \int_{v\geqslant p(x)} \mathcal{D}(v,d)dG(d|x)dF(x), \tag{1}$$

where $\mathcal{D}(p,d) \equiv D(p) + d$ for short, G denotes the cumulative distribution function for d, and $p(x)$ is the price as a function of realization x. As usual in models that exploit Gaussian structures (e.g., Vives, 2008; Bonatti and Hörner, 2017) we ignore the non-negativity constraints, and focus on interior outcomes where $p(x)$ follows from $0 = D(p) - S(p) - x$, with $x = s - d$.

Expanding the above surplus gives

$$\begin{aligned}
\mathbb{E}W &= \int_{x\in M} \int_{v\geqslant p(x)} D(v)dvdF(x) + \int_{x\in M} \int_{d\in N} \int_{v\geqslant p(x)} (d)dvdG(d|x)dF(x) \\
&= \int_{x\in M} \int_{v\geqslant p(x)} D(v)dvdF(x) + \int_{x\in M} \int_{v\geqslant p(x)} (ax)dvdF(x) \\
&= \int_{x\in M} \underbrace{\int_{v\geqslant p(x)} (D(v) + ax)dv}_{\equiv U(x)} dF(x).
\end{aligned}$$

Function $U(x)$ is the consumer surplus from the demand-supply realization x. The consumer in one location buys with one price instead of the others but does not know that price in advance. Hence, the surplus $\mathbb{E}W$ measures what the consumer can expect on average. For electricity, F may capture the share of the daily time when price $p(x)$ prevails, and the correlation structure captures the changes in the consumer's needs. The expected surplus $\mathbb{E}W$ is the relevant surplus measure in such situations.

Lemma 1 *Efficient trade increases (decreases) the consumer surplus if $U(x)$ is strictly concave (convex).*

Proof. For efficient trade: the market condition collapses to $\overline{x}$, distribution F becomes degenerate at $\overline{x}$, and then the surplus is just $\mathbb{E}W = U(\overline{x})$. Because F is a mean-preserving spread around $\overline{x}$, we see that the strict concavity of $U(x)$ implies $\mathbb{E}W < U(\overline{x})$. The strict convexity of $U(x)$ reverses the inequality. ■

We can make strong predictions by building on $U(x)$:

$$U'(x) = -p'(x)[D(p(x)) + ax] + \int_{v \geqslant p(x)} adv, \quad \text{and}$$

$$U''(x) = -p''(x)[D + ax] - p'(x)^2 D' - 2ap'(x),$$

$$= \underbrace{-p''(x)[D + ax]}_{(i)} \underbrace{-p'(x)[(1-\rho) + 2a]}_{(ii)},$$

where ρ is the pass-through rate

$$\rho \equiv \frac{S'}{S' - D'} = \frac{1}{1 + \frac{\varepsilon_d}{\varepsilon_s}},$$

with ε_d and ε_s being the elasticities of demand and supply in absolute value, respectively. We assume that the supply elasticity ε_s is finite, and then $\rho < 1$ is equivalent to saying that there is a demand response, $\varepsilon_d > 0$. With these observations, we can isolate the three effects for the consumer's surplus change, starting with pass-through:

Proposition 1 ***(Pass-through)*** *Assume that $D(p)$ and $S(p)$ are linear and that $\mathbb{E}(d|x) = \mathbb{E}(d) = 0$ (i.e., $r = \frac{\sigma_d}{\sigma_s}$). Then, it holds that the consumer surplus is higher under dispersed prices, $\mathbb{E}W > U(\overline{x})$, if the pass-through rate is less than unity ($\rho < 1$), i.e., if there is a demand response.*

Proof. With linear $D(p)$ and $S(p)$, $p''(x) = 0$ and thus term (i) in U'' is zero. Term (ii) is strictly positive if $a \geq 0$ which holds by $r = \frac{\sigma_d}{\sigma_s}$. Therefore, U is strictly convex. ■

With $\rho < 1$, and the assumptions made, the source of the consumer's welfare gain is that the consumer optimizes: the consumption level is responsive to prices, and therefore the surplus is a convex function of the price. The effect is conceptually the same as the one that drives concavity of the expenditure function and the convexity of the profit function in elementary microeconomics. The consumer's surplus gain from volatile prices was first documented by Waugh (1944), and it has been extended beyond quasi-linear settings in Turnovsky, Shalit and Schmitz (1980). Interestingly, in our setting the effect can be expressed with the help of the conventional pass-through rate ρ.[14] Intuitively, ρ measures incidence: the price deviates from the first-best, and the incidence of this depends on who can better respond to the deviation. The consumer surplus becomes more convex, i.e., the gain from the option to respond increases, if we increase ε_d or alternatively decrease ε_s.

The next result isolates the effect from the correlation of demand and supply:

[14]See, e.g., Weyl and Fabinger (2013) for a discussion of the concept.

Proposition 2 ***(Correlation)*** *In proposition 1 assume no demand response ($\rho = 1$) but add correlation: $\mathbb{E}(d|x) > \mathbb{E}(d) = 0$ (i.e., $r > \frac{\sigma_d}{\sigma_s}$). Then, the price dispersion continues to benefit the consumer, $\mathbb{E}W > U(\overline{x})$.*

Proof. Term (i) in U'' remains zero, and in term (ii) we have $\rho = 1$ so it becomes $-p'(x)2a$. Therefore U is strictly convex iff $r > \frac{\sigma_d}{\sigma_s}$. ■

When the consumer has inelastic demand, the pass-through term disappears by $\rho = 1$ and the consumption choices are given. Then, the consumer surplus depends on prices only through expenditures. The condition $r > \frac{\sigma_d}{\sigma_s}$ ensures that the occurrences of demand shifters are sufficiently aligned with supply shifters so that the expenditures are smaller under dispersed prices. For instance, air conditioning demand lines up with solar power availability.

We isolate next our final effect that depends on the excess demand defined by general $D(p)$ and $S(p)$. The excess demand, which we write with a slight abuse of notation as $X(p)$, is convex ($X''(p) > 0$) or concave ($X''(p) < 0$), depending on the curvatures of $D(p)$ and $S(p)$. This proves useful as the price function $p(x)$ inherits the concavity and convexity properties of $X(p)$.

Proposition 3 ***(Excess demand)*** *The conclusion of propositions 1 and 2 continue to hold for any demand response and positive correlation, if, in addition, it holds for general demand and supply that $X''(p) = D''(p) - S''(p) < 0$.*

Proof. Term (i) in the expression for U'' is now strictly positive because $X''(p) < 0 \Leftrightarrow p''(x) < 0$. Term (ii) remains positive from propositions 1 and 2, for any $\rho \leq 1$ and $a \geq 0$. ■

A concave excess demand means that the expected price level declines after introducing the mean-preserving spread to $\overline{x}$. Intuitively, the mean of dispersed prices is lower than the price under the law of one price. The effect captured by the excess demand is separate from that captured by pass-through because the latter arises from the consumer optimization even with no change in the expected price level, as isolated in proposition 1 with linear demand and supply. The effect from correlation remains also as a separate effect working through the expenditures, as isolated in proposition 2. To interpret proposition 3, consider a situation with inelastic ($D'' = 0$) and predictable demand $\sigma_d = 0$ together with a convex supply in price ($S'' > 0$). Then, the prices are dispersed due to supply shocks only. Trade, by the convexity of supply, reduces the peak prices at a slower rate than the rate at which the off-peak prices increase. The role of excess demand for the welfare impact of price stabilization has been noted the trade literature (Just et al., 1978), but we have not found formal statements of the effect.

3 Empirical implementation

We use micro-data on bids to buy and sell from three electricity wholesale markets for quantifying the equilibrium effects of a mandate of controlled size: we add $1GW$ capacity to each hour for trading allocations within each day. In Section 3.1, we describe the data preprocessing and the replication of actual market outcomes from the bid data. In Section 3.2, we introduce the experiment in which we run the market-clearing task using the bid data with the mandate for efficiency improvement. In Section 3.3, we report the descriptives of the data from the experiment, including the consumer, producer, and the total surpluses. In Section 3.4, we develop the covariates for explaining the consumer surpluses, including the convexity measure. The results of the regression with economic interpretations are in Section 3.5.

3.1 Data and the market model

We put together a data set of 162.7 million bids from the operators of three markets, CAISO (California), Nord Pool (Nordic), and OMIE (Spanish/Iberian) in 2015–2020.[15] The unit of observation is a bid for an hour in a day-ahead market, with typically a few thousand observations per hour in each market.

The markets differ in their approaches to technicalities of market clearing, 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. For example, in California there are in principle 3,000 locational markets while in the Nordics there is only a handful of possible price zones.

We consolidate the raw data from the operators into one coherent data set in which bids are defined as hourly price-quantity pairs. First, we use ancillary market data to exclude from the bids any resources that are committed to serve the real-time markets.

[15] Appendix A is the supporting material for data and quantitative analysis.

Second, the complex bids, which allow firms to express their ramping up and down costs, are deconstructed to single bids; 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 implemented ignoring the transmission constraints. The system equilibrium is conceptually well defined, i.e., it exists for all markets, although this equilibrium outcome is explicitly reported only by the operator in the Nordic market.[16]

We replicate the market-clearing task by a formal model that maps the bid data into market outcomes. The data consists of a set of demand bids, $(p_{i,h}, Q_{i,h})_{i\in\mathcal{D}_h}$, and a set of supply bids, $(p_{j,h}, Q_{j,h})_{j\in\mathcal{S}_h}$, for any given hour h, day, and market (for simplicity, the last two are left out from the notation). Let $Q^d_{i,h} \in [0, Q_{i,h}]$ be the quantity of demand bid $i \in \mathcal{D}_h$ activated in equilibrium, and, similarly, $Q^s_{j,h} \in [0, Q_{j,h}]$ for supply bid $j \in \mathcal{S}_h$. The total demand is then $Q^d_h = \sum_{i\in\mathcal{D}_h} Q^d_{i,h}$, and the total supply is $Q^s_h = \sum_{j\in\mathcal{S}_h} Q^s_{j,h}$. A uniform price auction can be efficiently solved through a linear program for the total surplus maximization, an idea dating back to Samuelson (1952).[17] This program gives us hourly prices such that the excess demand is zero, $X_h = Q^d_h - Q^s_h = 0$. Potential market power and other inefficiencies that may exist in the bid data are not addressed in any way: the program finds the efficient allocation and prices by hour, given the bids.[18]

The physical locality of demand and supply is an important constraint in all electricity markets, and thus the equilibrium price can vary by physical location within a market. Subject to this caveat, the system equilibrium obtained from our bid data can be tested by constructing system-level equivalents of prices and quantities from the locational data. For the Nordics, the system-level equivalents are reported by the market operator, and we can directly test, e.g., the match between the model output and actual prices (Table A.3). 99% of the modeled Nordic equilibrium prices are within €.38/MWh of the reported system prices; on average, the gap between the two prices is €.04/MWh. For Spain, we construct the mean of locational prices for each hour, and find that they differ by €.03/MWh from our model predictions for hourly prices on average in the data period. For California, the model price on average falls short of the mean of the locational prices by \$2.1/MWh. These findings are expected: the Nordic data is exactly about the system

[16] Appendix A.2 provides the detailed preprocessing steps, and an accompanying data set contains codes for replicating the steps.

[17] This is the basic method used by power exchanges (see e.g. Fabra, von der Fehr and Harbord, 2006).

[18] The formal program is in Appendix A.3.

equilibrium that our model seeks to replicate; the Spanish zonal system comes close to the full system equilibrium; and the nodal price data of California implies a greatest deviation from the system outcome.[19]

3.2 Counterfactual experiment: efficiency improvement

Turn next to producing the counterfactuals. Above, we found hourly prices from the bids so that $X_h = 0$ holds separately for each hour of the day, $h \in \mathcal{H}$, whereas next we do the same by aggregating over the hours of any given day: $\sum_{h\in\mathcal{H}} X_h = 0$. Thus, the objective is to maximize the daily total surplus, and we relax the hourly supply–demand balance constraints with a possibility to "trade" a net quantity Y between the hours of one day:

$$X_h = Q_h^d - Q_h^s, \quad \forall h,$$
$$-Y \leq X_h \leq Y \quad \forall h,$$
$$\sum_{h\in\mathcal{H}} X_h = 0.$$

Hence, Y is the size of the experiment, set at $1GW$. This quantity is small, ca. 1/50 of the total installed generation capacity in each market, which supports the assumption that the bids remain unaffected by the experiment. On purpose, Y is free of technology details, but it can be micro-founded, e.g., as a storage technology (see Appendix C.2).[20] We thus focus on allocative and gross surplus implications of a stylized mandate, leaving out investment costs.

3.3 Equilibrium impacts of the experiment

Table 1 offers a breakdown of the equilibrium impacts of the experiment as mean changes in quantities, prices, and surpluses.

The surplus measures are the textbook consumer and producer surpluses, obtained from the demand and supply bids. Bearing in mind that the final end-user surplus

[19]The location distribution of impacts from efficiency improvements is an interesting extension. It calls for a different approach dealing, e.g., with local market power; see Ryan (2021), Gonzales, Ito and Reguant (2022), Graf and Wolak (2022).

[20]Section 3.6 discusses the results from the storage model in detail. This model defines a relationship between a given Y and the size of the actual storage needed for the same effective impact. One key observation is that a daily storage delivers bulk of the efficiency gains (consistent with, e.g., Abrell, Rausch and Streitberger, 2019).

Table 1: Impact of 1 GW flexible technology

Area	Obs.	Share	Q	ΔQ	P	ΔP	Δ Consumer surplus	Δ New tech. surplus	Δ Total surplus
			GW		\$/MWh or €/MWh		Change in M\$ or M€ per year		
California	**All**	**1**	**26.53**	**-0.004**	**32.13**	**-0.23**	**114.15**	**55.64**	**62.17**
	Concave	0.33	25.10	-0.026	25.78	0.3	-16.27	16.05	18.04
	Convex	0.67	27.23	0.007	35.27	-0.5	130.68	39.61	44.14
Nordics	**All**	**1**	**41.24**	**0.004**	**28.06**	**-0.23**	**156.38**	**9.91**	**13.82**
	Concave	0.47	39.12	-0.003	28.61	0.26	-26.05	4.08	5.58
	Convex	0.53	43.13	0.01	27.58	-0.67	182.75	5.84	8.24
Spain	**All**	**1**	**26.74**	**-0.067**	**46.96**	**0.06**	**27.15**	**24.87**	**31.49**
	Concave	0.54	27.75	-0.065	49.84	0.33	-14.96	14.08	17.46
	Convex	0.46	25.57	-0.07	43.61	-0.27	41.86	10.8	14.03

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). Breakdown by observations is based on the convexity/concavity of the daily market (see Section 3.4 below for detail). 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.1.

depends on the structure of the retail market and on costs such as taxes, levies, and grid charges, which are all different across the three markets, we note that the consumer surplus changes in this analysis give one unified measure for the root of consumer benefits. In addition to the consumer and incumbent producer surpluses, there is the surplus to the new technology from efficiently operating $Y = 1GW$. This surplus is the total equilibrium arbitrage gain from the hourly price differences.[21] The surpluses in Table 1 are in millions of euros/dollars per year on average in our data period 2015-2022.[22]

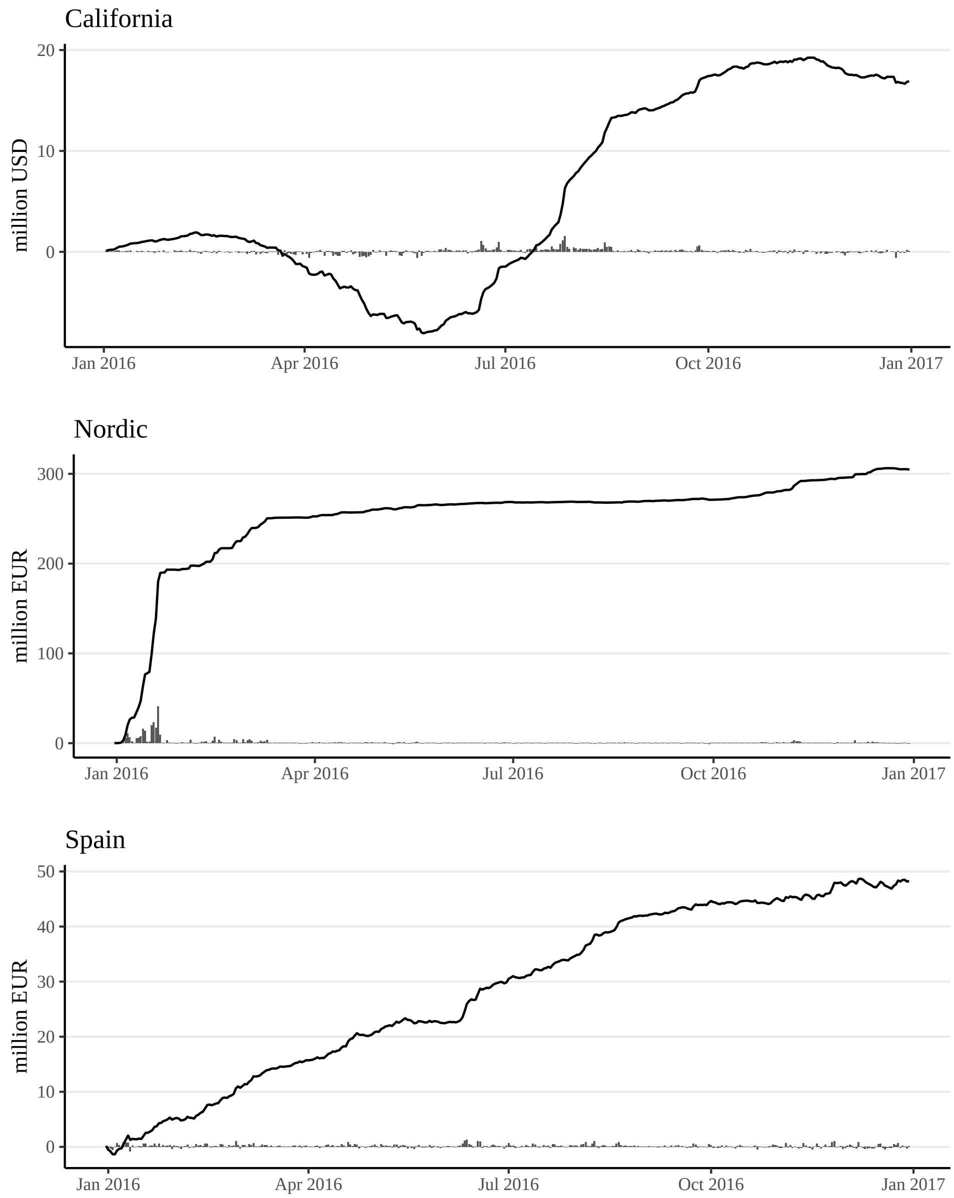
The mean annual total surplus gain is \$62.2 million in California, €13.8 million in the Nordics, and €31.5 million in Spain. For instance, in California the gain *ad infinitum* is ca. \$1.5 billion, with 4% interest rate, giving about \$1,500 per household, if one assumes that the added flexibility of $1GW$ is equivalent to a demand response from one million households (see Lawrence Berkeley National Laboratory, 2017). The bulk of the total gain is arbitrage surplus, and similarly so in the Nordics and Spain.

The total surplus is the gross social value, equal to what the new technology creates in terms of surpluses. The consumer surplus gain exceeds the gross social value in all markets – by more than ten times in the Nordics! Using the same calculation as just

[21] It is an empirical question if the technologies for arbitrage are used efficiently in actuality. Lamp and Samano (2022) find evidence supporting this conclusion for large-scale storage facilities in California.

[22] Appendix B unpacks the seasonal and annual changes in surpluses in the data period.

Figure 2: 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 original equilibrium. 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. (Data for other years is visualized in a similar manner in Appendix B.1.)

above for California, the consumers' gain is close to $4,000 per household in the Nordics. In California and Spain, these gains are ca. two times the social value. What explains the result and the differences in the magnitudes? Table 1 classifies days as "concave" and "convex", referring to our convexity measure of the excess demand used in the regression analysis of the next Section. The consumer surplus increases (decreases) on average in convex (concave) days. To introduce the economic meaning of this convexity, Figure 2 reports the change in consumer surpluses due to the experiment day-by-day (small bars) and its cumulative sum (solid lines) over the course of one illustrative year (2016). The three markets show notably different surplus developments over the year.[23]

In California, the hourly price differences within a day start to increase in the spring, with depressed day prices and peaking evening prices. The solar PV systems crowd out a mix of gas-fired generation when the sun rises but the gas-fired units must quickly ramp up when the sun sets.[24] In these situations, the supply is typically convex in prices (i.e., concave in quantities), and the demand is relatively inelastic (see Video, Panel A). Then, the excess demand is concave, and the efficiency improvement works against the consumer surplus, as it increases the daily price level. Consumers lose day-by-day, until the trend is reversed later in the summer. A higher demand for cooling pushes the power system closer to full capacity, and the concave part of the supply curve applies (i.e., convex in quantities, see Video, Panel B). The efficiency improvement reduces the peak power generation and this lowers the peak prices more than what the prices rise during the off-peak periods. In the end, over the year, the consumer surplus remains positive.

In the Nordics, the daily price dispersion is small for a large part of the year, as the hydro resource provides flexibility for counterbalancing the wind power intermittency and demand variation.[25] Nearly all of the consumer surplus 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 the supply is concave in prices (i.e., convex in quantities, see Video, Panel C). $1GW$ additional capacity for reallocating loads reduces the impact of the market-level supply shortage in production and this brings consumer surplus gains that are significantly larger than for the other markets.

In Spain, the data suggest that the demand is more elastic than in the other markets, bringing stability to the surplus gain development over the course of the year: the demand elasticity reduces price peaks and also prevents prices from falling quickly in a positive supply shock. Intuitively, the demand and supply come close to being linear (see Video, Panel D), suggesting that the mandate has a moderate impact on the price levels – an alluring consistency with the theory prediction.

[23] Appendix B reports similar figures for all years in the data.

[24] See, e.g., Borenstein and Bushnell (2015) for a discussion of the phenomenon.

[25] In a typical year, ca. 50% of power is generated by hydro power in the Nordics. For example, in 2017, the share was 20% in California and 8% in Spain (EIA, Eurostat).

We turn next to quantify the contribution of the convexity of excess demand, together with the pass-through rate and correlation, to the consumer surpluses using a regression model including all three determinants.

3.4 Reduced form

Motivated by the theory, we consider a linear-regression model for the change in the daily consumer surplus:

$$\Delta CS_t = f(\text{pass-through}_t, \text{correlation}_t, \text{convexity of excess demand}_t, \text{error}_t). \quad (2)$$

The unit of observation on the left is the change of the daily demand-side surplus, ΔCS_t, calculated from the demand bids before and after the technology experiment. The covariates included follow from our Propositions 1-3, constructed from the data as follows:

Pass-through

The pass-through rate measures how the demand and supply respond to the price change induced by the experiment. We obtain a measure of $\rho = \frac{1}{1+\frac{\varepsilon_d}{\varepsilon_s}}$ from the bid curves for each hour h at date t by taking a $\pm 1\%$ quantity change around the equilibrium quantity and observing the corresponding changes in prices from the bid curves. The unit of observation used in the regression is the mean of ρ over the hours in day t.

Correlation

How the demand shocks line up with supply shocks impacts the consumers' expenditures. The experiment compresses the price dispersion, which can benefit or hurt the consumers, depending on the correlation structure. We obtain a measure of the correlation structure from the hourly bid curves. We take a given fixed price and read the demanded and supplied quantities from the original bid curves for each hour of a day, giving 24 observations from each curve. We then vary the price, using the actual equilibrium prices, which gives 24×24 matrix per day both for the demand and supply quantities. From this data we obtain the standard deviations and correlations of demands and supplies at each price level. We take the mean values for the standard deviations and correlations, and use these as the daily observation in the analysis.[26]

[26] The correlations structure can be defined in alternative ways with little impact on the main results. For example, we have used only one price level, say 100 \$/€ per MWh, for generating the quantity data.

Convexity of excess demand

We apply Jensen's inequality to an empirical excess demand to obtain so-called Jensen's gap, a measure of convexity, for any given day. This is the unit of observation in the analysis. Consider next the construction of the daily excess demand.

In Fig. 3, Panel A depicts all bid data hour-by-hour as the demand and supply graphs for two distinct days in California. On the left, the data is from spring 2020, with the supply curves showing convexity in prices. On the right, the data is from summer 2020, and this time we observe that the supply curves show concavity in prices.

Panel B depicts (parts of) excess demands for each hour, derived from the demand and supply schedules shown in Panel A. Each hourly excess demand has its own equilibrium price, the dots on the horizontal axis, i.e., at each such price $X_h = 0$. Using these curves for an efficiency experiment, we can look for one price that gives $\sum_{h \in \mathcal{H}} X_h = 0$, i.e., the daily excess demand is zero. This amounts to assuming an unlimited capacity for reallocations, captured by a sufficiently large Y in program (4). Visually, all hourly graphs are connected by a vertical line at this price level.

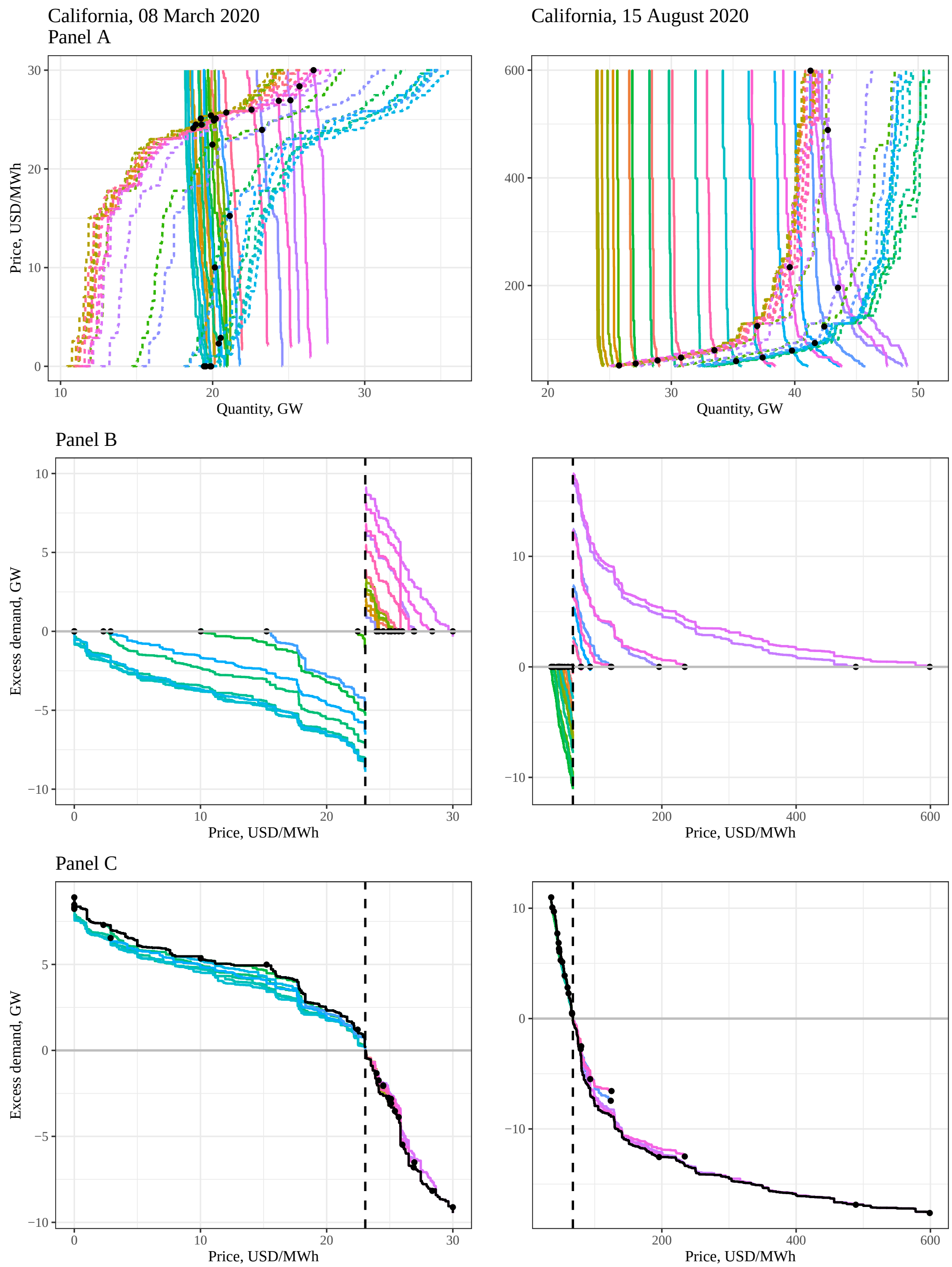
Panel C organizes the data from Panel B to obtain one graph to represent the daily excess demand. At the equilibrium price, the value is zero. At a lower (higher) price, there is positive (negative) excess demand. If all hourly markets had the same primitive demand and supply, as in equation (1) of the theory model, the family of curves in Panel C would collapse to become one representative curve. The variation in the curves calls for an approximation giving a representative curve. We obtain the approximation by an upper envelope of the curves for positive values and by a lower envelope of the negative values. These envelope graphs are depicted in Panel C.[27]

We construct the envelope curve for each day and obtain a measure of convexity, i.e., Jensen's gap, from this. Let $\mathcal{X}(p)$ be the step function given by the envelope curve for day t. Then, using $\mathcal{X}(p)$, the price given by this function for any given quantity x is

Panel A of Fig. 3, to be discussed in more detail just below, shows the families demand and supply curves for two days: the shocks introduce mostly additive shifts of the curves. Scanning through a broad range of prices is intended give some weight also to the possibility that the shocks alter the shape of the curves.

[27]We may, e.g., alternatively construct a mean of the curves in our analysis. We have not found important differences in results caused by the approximation method of the excess demand.

Figure 3: Illustration of bid and excess-demand curves



Notes. Figures are for the California day-ahead market in two days. Panels on the left are from 8 March 2020 and panels on the right from 15 August 2020. Panel A (top row) shows demand curves (dotted lines) and supply curves (solid lines) of all hours with the market equilibria denoted by black dots. The excess demand curves of each hourly market, starting from the original market prices, are shown in Panel B (middle row). Panel C (bottom row) shows the same excess demand curves starting from the price at which daily excess demand vanishes, and the upper and lower envelope curves that approximate the aggregate excess demand curve.

defined by $\mathcal{P}(x) = \mathcal{X}^{-1}(x)$, which defines Jensen's gap, G, as

$$G \equiv E[\mathcal{P}(x)] - \mathcal{P}(E[x]),$$

where $E[x] = 0$ because the daily excess demand is zero. Price $\mathcal{P}(E[x])$ is thus the efficient price, and $E[\mathcal{P}(x)]$ is the mean of the actual (original) prices. A strictly positive G, associated to a strictly convex excess demand, measures the potential of the prices to decline due to the efficiency. The mean value of G in California is \$1.43/MWh, but ca. one-third of the days show negative G values. In the Nordics and Spain, positive and negative G have close to equal frequencies; see Table 1.[28]

3.5 Regression results

We estimate the linear regression model in (2). In Table 2, the covariates are added successively in columns (1)-(5) to observe the movement in the total variation explained and the stability of the coefficients, in the spirit of the identification by observables approach (e.g., Altonji, Elder and Taber, 2005). We take the price-level effect, i.e., the convexity of excess demand curve as the main effect: it captures the bulk of the variation in all markets, and the coefficient remains precise and stable across specifications. The results are robust to a reordering of the covariates, i.e., to a change in the main effect, suggesting that the covariates are not correlated.[29] Possible omitted variables, linearly dependent on the covariates, could be analyzed as in Oster (2019) but the total variation explained suggests that (hypothetical) omitted variables could not eliminate the main effect to a notable degree.

The results for California (Table 2, Panel A) offer a clear message: the convexity measure explains 90 per cent of the total variation, and the remaining coefficients are inconsequential for the total variation of the buyer-side surplus. In the Nordics (Table 2, Panel B), we observe that the convexity, similarly to California, explains almost all of

[28]The descriptives of all covariates are in Appendix B.2.

[29]See Appendix C.1 for this robustness analysis. For the Nordics, the pass-through term explains a substantial share of the variation. We unpack this result in the Appendix, and show that it follows because the pass-through term is badly defined in situations where both demand and supply are extremely inelastic. These situations are rare but economically significant, and they are correlated with under-supply situations. Therefore, the pass-through term seemingly explains some part of the variation. For this reason, we use the estimation results in column (4), instead of column (5), when discussing the results for the Nordics.

Table 2: Explaining the change in consumer surplus

A. California

	(1)	(2)	(3)	(4)	(5)
Convexity	0.226 (0.002)	0.226 (0.002)	0.226 (0.002)	0.226 (0.002)	0.229 (0.002)
Variation, Demand		-0.004 (0.008)	-0.007 (0.009)	0.0003 (0.010)	-0.005 (0.011)
Variation, Supply			-0.019 (0.013)	-0.018 (0.013)	-0.032 (0.015)
Correlation				-0.087 (0.056)	-0.017 (0.062)
Passthrough					0.274 (0.326)
R^2	0.90050	0.90051	0.90061	0.90073	0.90798
Observations	2,045	2,045	2,045	2,045	1,844

B. Nordics

	(1)	(2)	(3)	(4)	(5)
Convexity	1.06 (0.010)	1.07 (0.011)	1.06 (0.011)	1.06 (0.011)	0.740 (0.013)
Variation, Demand		-0.027 (0.013)	-0.052 (0.014)	-0.056 (0.014)	-0.018 (0.012)
Variation, Supply			0.142 (0.033)	0.129 (0.035)	0.112 (0.028)
Correlation				0.102 (0.076)	0.088 (0.062)
Passthrough					-24.1 (0.692)
R^2	0.82786	0.82821	0.82963	0.82977	0.89136
Observations	2,192	2,192	2,192	2,192	2,150

C. Spain

	(1)	(2)	(3)	(4)	(5)
Convexity	0.138 (0.004)	0.145 (0.004)	0.151 (0.004)	0.152 (0.004)	0.147 (0.004)
Variation, Demand		0.020 (0.005)	0.032 (0.006)	0.029 (0.006)	0.033 (0.006)
Variation, Supply			-0.046 (0.005)	-0.050 (0.006)	-0.047 (0.006)
Correlation				0.041 (0.021)	0.104 (0.022)
Passthrough					-0.398 (0.047)
R^2	0.40631	0.40981	0.42913	0.43013	0.45238
Observations	2,192	2,192	2,192	2,192	2,051

Notes. Panels document reduced form regression in eq. (2) by market area. The dependent variable is the change in the daily consumer surplus, measured from the demand side bids before and after the technology experiment. Convexity is Jensen's gap calculated from the daily excess demand. Variation Demand and Variation Supply are standard deviations obtained, together with Correlation, from the daily correlation matrices for quantities from the bid curves. Pass-through is the pass-through rate using the empirical estimates of local elasticities at equilibrium from the bid curves.

the variation. The results for Spain (Table 2, Panel C) confirm the same patter, i.e., they show the importance of the convexity measure, but the impact of the other covariates is more nuanced. The correlation structure, including demand and supply variation and their correlation, contributes by 3% to the explained variation, with all elements having precise estimates. The pass-through covariate explains 2% of the total variation.

The estimate of the convexity term means that when the mandate changes the daily price expectation by one euro/dollar, the daily consumer surplus changes by .226 million in California, 1.06 million in the Nordics, and .147 million in Spain. The mean value of the convexity covariate in California is \$1.43 , €.29 in the Nordics, and -€.04 per MWh in Spain, calculated over the data period 2015-2020 (see Table B.3). Multiplying with the coefficients for convexity in Table 2 and translating from daily to annual mean values gives predictions of consumer surplus changes: \$118 million U.S. dollar in California, €113 million euro in the Nordics, and -€2.3 million euro in Spain. The experiment shows that, controlled for market size, the consumer benefit of the efficiency improving technology is the largest in California whereas the impact in Spain remains modest (cf. Table 1).

3.6 Robustness

The definitions of covariates introduce some measurement errors. The hourly supply and demand curves may experience other than additive shifts, and the daily covariates are obtained from the hourly observations. In addition, Jensen's gap is calculated from an approximation. We observe that the convexity measure captures the total surplus variation to an extent that the errors in the other covariates should not have substantial implications for the results; in particular, there is no general evidence of correlation between the sets of covariates. Thus, we find that the price-level effect, captured by the convexity of excess demand, is robust in our assessment.

A more basic concern relates to the design of the experiment. Is the $1GW$ experiment "small" to justify the assumption that the bids in the market can be taken as given, i.e., unaffected by the experiment? The concern links to the market structure and how potential strategic bidding may be affected. However, even under perfect competition the bids could change in response to a new capacity: for instance, firms may withdraw sets of bids if the new prices after the experiment do not cover ramp-up cost of plants (see, e.g. Reguant, 2014). This concern is bigger, the larger is the experiment. In the next

Section, we consider experiments of varied sizes and find that the impact on consumer welfare remains the same for experiments in which Y is reduced to $.1GW$. We also analyze a considerably larger experiment to offer a comparison to Butters, Dorsey and Gowrisankaran (2021).

One limitation of the market-level approach of this paper is that it cannot answer where the new technology should be installed. For instance, a storage technology may have a large impact on prices in certain physical locations, leading to a larger market-level impact than indicated by our system-level approach. The physical location distribution of technologies is an important part of hands-on planning, and addressing the issues related to locality calls for a different approach (e.g., Graf and Wolak, 2022).

Finally, our new technology is a reduced-form, generic arbitrage capacity. In Appendix C.2, we introduce more structure and model explicitly one technology: a battery storage with a limited capacity and round-trip efficiency losses from the conversion of energy to and from the battery. This richer model tracks the chronological order of trades and the related losses. It confirms the results obtained for the generic $1GW$ mandate for California and the Nordics: the same consumer surplus impact is achieved under $1.3GW$ storage in California (i.e., the size of the actual mandate for 2024), and closer to $2.5GW$ storage in the Nordics. Thus, the mandate translates into different storage sizes in the locations, but the conclusions for the equilibrium impacts remain largely intact. The technology constraints do not lead to large deviations because the daily battery recharging and usage patterns are in congruence with the supply and demand conditions in these locations. The situation is different for Spain where the chronological order imposed on trade and the technology constraints lead to a significant reduction in the consumer surpluses. This finding further supports the conclusion the impacts of technology mandates are more limited in Spain.

4 Policy context

Table 3 reports marginal impacts on the annual mean surpluses from increasing Y in small steps of $100MW$ (i.e., one tenth of the original experiment size). The market return for the first addition of Y differs between the markets, from 63.2 million dollars in California to 37.5 million in Spain and 17.6 million euros the Nordics. The numbers are expressed in euros or dollars per $1kW$ of capacity for a comparison with the main experiment in which, for example, the return to a one-step $1GW$ was 62 million in California, almost the same as for the first $100MW$. In contrast, the decline in equilibrium returns is larger in the other locations. In fact, the marginal return becomes negative after $1GW$ in the Nordics, after $2GW$ in Spain, and after $3GW$ in California.

Table 3: Technology impact: marginal values

Capacity	Δ technology surplus			Δ consumer surplus		
GW	California	Nordic	Spain	California	Nordic	Spain
0.1	63.2	17.6	37.5	122.2	268.4	13.3
1	41.7	4.3	14.3	98.3	84.4	24.1
2	22.8	-1.1	0.7	88.4	44.5	13.2
3	8.5	-2.8	-6.1	78.5	24.5	15.7
4	-2.0	-2.8	-8.1	65.4	14.3	12.1
5	-10.2	-2.2	-7.4	56.0	8.2	10.5

Notes. The marginal value of the new technology and the marginal change in consumer surplus for an additional unit of capacity at the specified capacity level. All changes in annual mean values in the data period, measured in units of million U.S. dollar or euro per GW (equal to dollar or euro per kW).

Quantitatively, the strongly declining technology returns are in agreement with the findings in Butters, Dorsey and Gowrisankaran (2021) who consider only California in a framework that is designed for an equilibrium analysis of a large-scale storage investments. They find that the policy mandate for installing ca. $5GW$ of utility-level storage would, under the projected decline in the investment cost, be reached only in 2044. Our results confirm the finding that the market surplus is not sufficient to induce any significant storage capacity investment. The result is even stronger for the Nordics and Spain.

In contrast to the technology surplus, the demand-side surplus gain continues to increase at all levels of Y considered (Table 3), at the expense of the incumbent producer surplus. The result is notable in Butters, Dorsey and Gowrisankaran (2021), and our analysis confirms the same result for the Nordics and Spain.

Policy makers often decide on the portfolio of capacities, and procure the capacities by various capacity mechanisms (Fabra, 2018; Joskow, 2019; Grubb and Newbery, 2018; Wolak, 2021*b*,*a*). For concerns about the security of supply, the price level, and well as carbon emissions, it is critical to evaluate the equilibrium impacts of new capacity, including investments in renewable energy and storage capacities. European energy crisis is an example of a situation where technologies that bring flexibility produce greater value for society than what the market return of the technologies reflects. Policy intervention can then be efficient (Gerlagh, Liski and Vehviläinen, 2022). In the energy crisis, the market lacks capacity, so the technology mandates lower the market price, which is one way to implement price control. In normal times, the market is more often in a situation of excess capacity, and then the mandates can raise the general price level faced by the consumer. However, the latter is a minor problem if the mandates prevent prices from escaping above the acceptable limit.

California has taken the biggest steps in the direction of increasing the share of renewables, implying the largest gains from technologies that live on the price differences coming both from over- and under-supply situations (visible in trends, Appendix B.3). The final impact on consumers, according to our results, depends on the relative frequency of the supply situations. The Nordic market is an example of a system in which gains from reducing price differences coming from under-supply cases, but the future may be different.

5 Concluding remarks

Do consumers gain when new technologies improve the efficiency of goods trade? The answer is less obvious than what one may read from the evidence on the benefits of technologies reducing information and other trade frictions. The equilibrium impacts are necessary inputs both for private and public policy decisions in markets where technology portfolios are regulated. How the short-run surpluses depend on the technologies is important if the technologies in the market are regulated or subsidized. This observation is not new (e.g., Borenstein and Holland, 2005), but our breakdown of surpluses into their sources is novel. In particular, the convexity of excess demand for capturing the price-level effects of trading technologies has gone unnoticed in the literature.

As new technologies improve price-responsiveness, they may limit market power (Joskow and Tirole, 2007; Wolak, 2019) and thus have implications for policies on competition. 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 incumbent producers.

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Online Appendix

Table of Contents

A Data and quantitative analysis

The Data Set containing all the codes to replicate the analysis and a sample of the data is available through this *link*.

A.1 Data sources

The raw data can be obtained from the following sources:

1. CALIFORNIA: CAISO, http://oasis.caiso.com
   The data is collected from OASIS server via the API-interface. The bids are collected from `Public Bids` and `Public Convergence Bidding` data categories. In addition we use `Ancillary Services`, and `System Load and Resource Schedules` data.

2. SPAIN: OMIE, http://www.omie.es
   The data is obtained from OMIE server. We use the `datosftp/public cbc` -files.

3. NORDIC: Nord Pool, http://www.nordpoolgroup.com
   The data is from the ftp-server of Nord Pool (access requires a licence). We use the data from the `System price bid curves` -folder.

The raw data consist of bid data and supporting data required in the preprocessing of data. Table A.1 gives summary statistics of the final bid data set after cleaning and preprocessing.

Table A.1: Bid data statistics

	Data period	Hours with data	Number of bids Demand	Supply	Total
California	03/03/15–12/31/20	49,080	12,632,453	42,622,255	55,254,708
Nordic	01/01/15–12/31/20	52,608	30,875,292	45,709,770	76,585,062
Spain	01/01/15–12/31/20	52,608	7,727,599	23,127,454	30,855,053

Notes: A bid in our data set is an anonymous price–quantity pair for a given hour in a given market. Data for some days or hours is missing or has been removed in the preprocessing e.g. because of incomplete or erroneous data. Data for California not available prior to 3 March 2015.

We follow the steps outlined below to obtain the equilibrium prices and quantities from the supply and demand bids for each hour of the day in the day-ahead markets. All steps are implemented with R and the codes to replicate the steps are included in the Data Set.

A.2 Preprocessing of data

We process the raw data obtained from the market operators to obtain one coherent data set that is an input to the market equilibrium and counterfactual computations. Each bid in our final data set is a price–quantity pair for one hour. We discuss below the detailed assumptions that we have made in the course of data processing by the market area.

California

Ancillary services. The initial allocation of resources in electricity markets is done in the day-ahead energy market where the bulk of the quantities are traded. However, market operators also need to take care, in real-time, of demand and supply shocks that realize after the day-ahead market clears. In California, the operator, CAISO, assesses the quantities of *ancillary service* capacities needed for this and procures the required amounts simultaneously with the clearing of the day-ahead energy market. Each bidder in CAISO can offer the same resource to the day-ahead energy market and potentially to one or many of the ancillary services markets. If the market operator selects a resource to any of the ancillary markets, then the bids from that resource are not included in the energy market calculation. As our interest lies in the energy market, we isolate the effects of the ancillary markets as follows: First, we collect the quantities of procured ancillary services by the hour as reported by CAISO. Second, we use the ancillary service market bid data to identify the least expensive bids and the associated resources to meet the hourly service requirements on each of the ancillary service markets. Third, these identified resources, whose bids we accept in one of the ancillary service markets, are made unavailable in the other markets. To avoid conflicts in deciding which resources are used where, we use CAISO's cascading hierarchy of the markets: Regulation Up, Spinning Reserve, Non-Spinning Reserve, and finally the day-ahead Energy market[30].

Locational bids. Each bid submitted to CAISO is linked to a node of the power network. There are around 3,000 nodes, and for each of them CAISO calculates a locational marginal price that takes into account the transmission constraints between the nodes. In our quantification, the geographical location of the bids is ignored to obtain

[30] CAISO applies a more detailed method where the same resources can be partially allocated to different markets as long as the capacity of the resource in total is not exceeded. Source: CAISO, Business Practice Manual for Market Operations, Version 44, 2015.

the system equilibrium which is comparable to that in the other markets. This approach is similar to the calculation of *system marginal cost of energy* (SMEC) that CAISO reports[31]. There are also imports and exports from CAISO to the neighbouring market areas. We take reported trade to/from CAISO in the day-ahead market, and add the net trade as one bid per hour to our data set[32].

Bid types. CAISO offers a variety of bidding options: *Economic bids*, *multi-stage bids*, and *convergence bids*[33]. Economic bids consists of a price–quantity pair that feeds directly our computations. With multi-stage bids generators can submit alternative schedules: For example, a power plant can be offered for the whole day or the same plant can be offered only for the peak hours but with a higher bid price. Such schedules are accepted only if the market price for all hours of the bid is above the bid price. The data does not identify which of the schedules are accepted; we systematically select the last schedule offered by the bidders and ignore the other schedules[34]. Convergence bids, often called virtual bids, are financial instruments between day-ahead and real-time markets. They are included in the determination of the day-ahead market prices, and we merge them together with the physical bids. Finally, we also convert all bids to simple hourly bids.

Nordic market

The data on equilibrium outcomes in the Nordic market comes close to the outcomes that our model is designed to produce. The market operator, Nord Pool, runs an energy only exchange where hourly supply and demand bids in the Nordic area are geographically attached to one of the 12 price areas. Nord Pool carries out two separate rounds of market clearing: one for each price area and another for a system-wide reference price, the *system price*. In the system price calculation bids from all price areas, regardless of their location, form a single supply curve and a single demand curve for each hour. We

[31]SMEC price is calculated over a *reference bus* that varies across hours in ways that are not disclosed. In price comparisons below, we use the average of SMEC prices across all nodes.

[32]CAISO provides also bid-level data on imports and exports, but the format does not allow the reconstruction of transmission flows.

[33]There area also *self-scheduled bids* where the bidder is a price taker; we assign either minimum or maximum price to such bids, and treat them then as other economic bids.

[34]We have compared the model generated market price realizations with the market outcomes: on average, this simple rule matches better with the data than other fixed orderings or randomization of the order.

take the individual bids underlying the aggregate bid curves as data.

In addition to the simple bids for one hour, Nord Pool has *block bids* that combine a fixed quantity and price over a period of several hours. In contrast to California, the power exchange reports the total quantities of the accepted block bids by the hour, but not the full universe of submitted block bids. This latter property can have an effect on the counterfactuals that we produce, although the effect should not be large based on the small impact of block bids on the baseline allocations. In addition, Nord Pool reports the total net trade flow from the surrounding regions through the transmission interconnections. We incorporate block bids and trade flows by adding corresponding single bids to each hour.

From 3 June 2020 the Nordic market has been served by another exchange, EPEX SPOT, for which we lack the market clearing data. As the trade through EPEX SPOT comprises of only less than 4% of Nord Pool's annual volumes in 2020 the impact on welfare measures can be expected to be minimal.

Spain

Like in the Nordic market, our model produces a close replication of the equilibrium outcomes in the Spanish market, but there are some discrepancies in the way market bids are collected. The operator, OMIE, has special rules to account for e.g. ramping-up and down restrictions, so the caveat from above applies: the actual bids are divided into accepted and non-accepted sets using rules that are not fully disclosed. Our model replicates precisely the actual equilibrium but the counterfactuals, if they were produced by OMIE, could differ from ours given the additional rules for market clearing.

Finally, we note that the data from OMIE includes also bids from Portugal which we include in the analysis. In 2011–2020 the prices for Spain and Portugal coincided over 90% of the time, i.e. at those hours there was only one price for the whole area.

A.3 From data to market outcomes

We have the data from the three markets for 2015–2020 which we use to replicate historical market prices and compute the counterfactuals. In total, the optimization is solved over 200,000 times. Each individual optimization problem has typically 15,000–35,000 variables (the bid data) and 24 constraints (hourly balance limits), and is easily solvable with any modern LP-solver. We use the Mosek-solver (http://mosek.com) for which it takes less than one second to solve one optimization, i.e., one day allocation.

A.3.1 Replication of market outcomes in the data

We replicate the market-clearing task by a formal model that maps the data to market outcomes. The data consists of a set of demand bids, $(p_{i,h}, Q_{i,h})_{i\in\mathcal{D}_h}$, and a set of supply bids, $(p_{j,h}, Q_{j,h})_{j\in\mathcal{S}_h}$, for any given hour h, day, and market (for simplicity, the last two are left out from the notation). Let $Q^d_{i,h} \in [0, Q_{i,h}]$ be the quantity of demand bid $i \in \mathcal{D}_h$ activated, and, similarly, $Q^s_{j,h} \in [0, Q_{j,h}]$ for supply bid $j \in \mathcal{S}_h$, maximizing the total surplus in a linear program:

$$
\begin{aligned}
\max_{\left\{Q^d_{i,h}, Q^s_{j,h}\right\}} \sum_{i\in\mathcal{D}_h} p_{i,h}Q^d_{i,h} &- \sum_{j\in\mathcal{S}_h} p_{j,h}Q^s_{j,h} \qquad (3)\\
\text{s.t.} \quad Q^d_h &= \sum_{i\in\mathcal{D}_h} Q^d_{i,h}, \quad Q^d_{i,h} \in [0, Q_{i,h}]\\
Q^s_h &= \sum_{j\in\mathcal{S}_h} Q^s_{j,h}, \quad Q^s_{j,h} \in [0, Q_{j,h}],\\
X_h &= Q^d_h - Q^s_h = 0.
\end{aligned}
$$

The market price is the shadow price of the constraint that supply equals demand, i.e. that the excess demand is zero, $X_h = 0$.

A.3.2 Counterfactual outcomes: effect of mandates on equilibrium

The model in (3) finds hourly prices from bids so that $X_h = 0$ separately for each hour of the day, $h \in \mathcal{H}$, whereas the model in (4) does the same by aggregating over the hours of any given day: $\sum_{h\in\mathcal{H}} X_h = 0$. The objective is now

$$
\max_{Q^d_{i,h}, Q^s_{j,h}} \sum_{h\in\mathcal{H}} \left[\sum_{i\in\mathcal{D}_h} p_{i,h}Q^d_{i,h} - \sum_{j\in\mathcal{S}_h} p_{j,h}Q^s_{j,h}\right], \qquad (4)
$$

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

$$
\begin{aligned}
X_h = Q^d_h - Q^s_h, &\quad \forall h,\\
-Y \le X_h \le Y &\quad \forall h,\\
\sum_{h\in\mathcal{H}} X_h = 0.&
\end{aligned}
$$

Note that now the excess demand, as read from the original bid curves, for any given hour can deviate from $X_h = 0$.

A.4 Replication results

Table A.2 presents summary statistics for the equilibrium outcomes from the model in Section A.3.1. The mean annual value traded through the day-ahead markets is \$8.1 billion in California, €10.5 billion in the Nordics, and €11.2 billion in Spain.

Table A.2: Summary statistics of market outcomes

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Equilibrium prices							
California (\$/MWh)	49,080	32.37	30.06	0.00	23.29	36.50	1,000.00
Nordic (€/MWh)	52,608	28.30	13.91	0.00	20.30	37.50	200.00
Spain (€/MWh)	52,608	46.90	14.75	0.04	38.12	56.97	102.00
Equilibrium quantities							
California (GW)	49,080	26.53	5.31	17.42	22.54	28.95	49.82
Nordic (GW)	52,608	41.24	8.02	24.03	35.24	46.80	65.26
Spain (GW)	52,608	26.74	4.77	14.72	22.93	30.30	42.98

Notes. Summary of hourly values of equilibrium prices and quantities as calculated by the model. Data from 2015–2020 for those dates where data is available.

To validate the preprocessing steps described above, we compare the equilibrium price outcomes from our model with the historical market prices.

California. The comparison is between the historical hourly averages of the nodal market prices obtained from CAISO and the prices from our model. On average, the model prices are slightly lower than the average of the nodal prices (see Table A.3). This is as s expected: we relax both the transmission constraints between the nodes and the ramp-up and ramp-down schedules, which should lead to lower average prices. However, the model does capture within a day price variation, essential for our quantifications; see Figure A.1, Panel A. for an illustration. Here, imperfect modeling of ancillary services may contribute to the differences during the periods with peak prices.

Nordic. The prices from our computations match the day-ahead market prices reported by the operator almost one-to-one, see Table A.3 and Figure A.1, Panel B. The distribution of the difference between our model price and the reported system price shows a very small upward bias which potentially results from differences in tie-breaking rules for bid curves that coincide in ways that produce multiple equilibria. The differences are inconsequential.

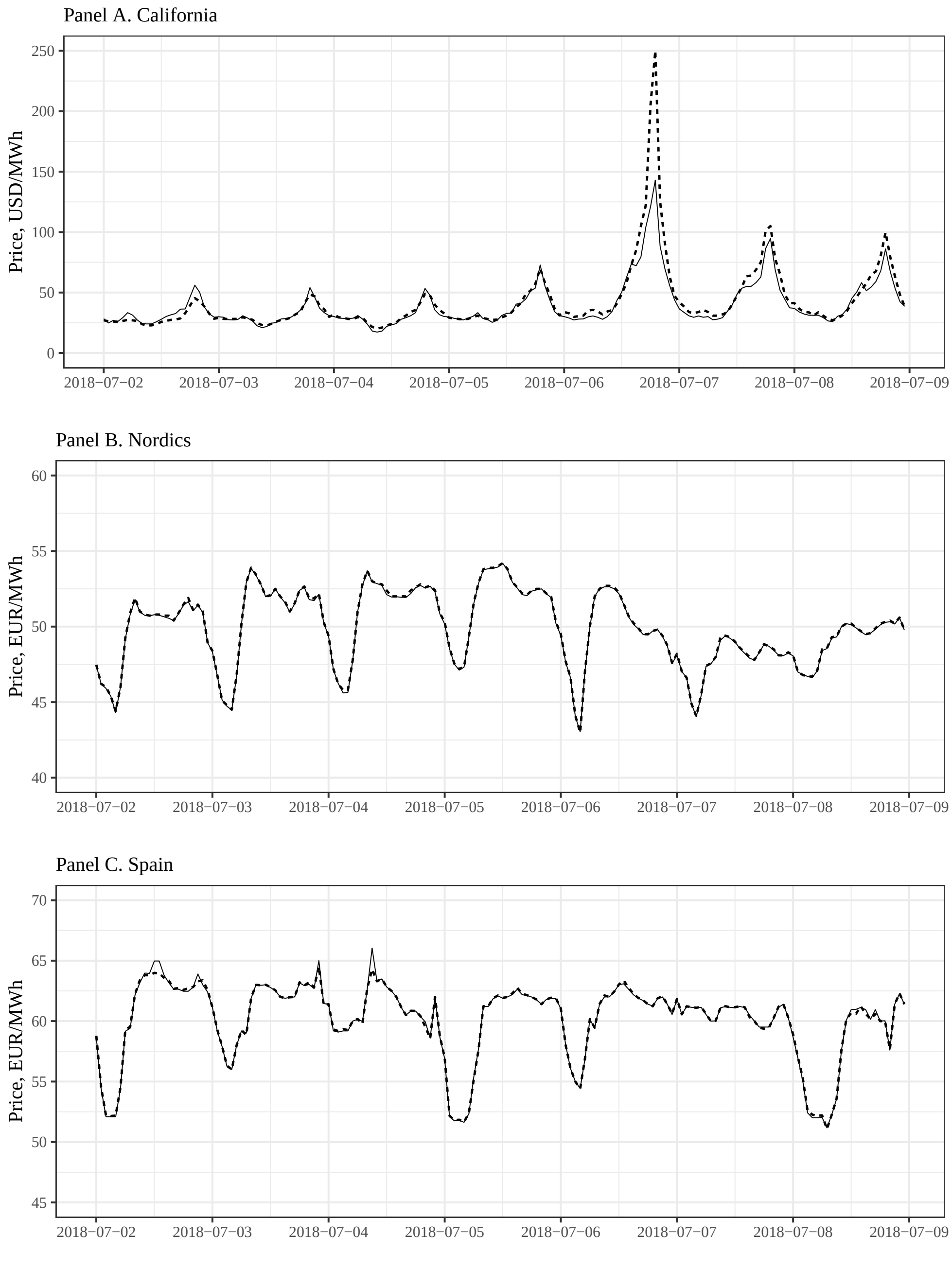
Spain. As in the Nordic case, the discrepancies between the reported and calculated prices are very small in Spain, see Table A.3 and Figure A.1, Panel C. This is not surprising: The European day-ahead electricity clearing is done simultaneous with the same clearing algorithm (EUPHEMIA) for 25 countries that closely resembles our model. The minor deviations likely relate to the additional assumptions made in the data preprocessing stage.

Table A.3: System-level prices from the bids

Area	5 %	50 %	95 %	Mean
California	-12.018	-1.606	4.461	-2.099
Nordic	0	0.031	0.133	0.038
Spain	-0.318	0.025	0.350	0.033

Notes: Reported values are the 5% and 95% quantiles, median and mean from the hourly differences between the model price and the historical price for the whole data period (see Table A.1). The historical price in the Nordics is the system price (up to 3 June 2020, after which a comparable prices is not available). The historical price in Spain is the mean price by the hour across the Iberian price zones. For California, the historical price is the mean energy price over the nodes by hour.

Figure A.1: Illustration of the hourly energy prices



Notes: Comparison between the historical hourly day-ahead market prices (solid lines) and model prices (dashed lines). In Panel A. California, historical prices are the mean of the hourly nodal energy prices (SMEC). In Panel B. Nordics the market operator reports direct equivalent to our model price, i.e., the system price. In Panel C. Spain, the historical prices is the mean of the Spanish and Portuguese area prices. Excerpt of data for the week starting on Monday 2 Jul 2018.

B Counterfactual experiment

B.1 Consumer surplus changes

Table B.1 presents the changes in consumer surplus that result from the addition of $1GW$ capacity of efficiency improvements to the daily day-ahead market using the model in Section A.3.2. The comparison is between the replicated market outcomes (with no efficiency improvements) and the counterfactual with $1GW$ capacity added. Table B.2, and Fig. B.1, B.2 and B.3 document the seasonal changes in consumer surplus for the same experiment. In California, the convexity measure and consumer surplus changes are systematically negative in Spring and positive in later in Summer. This reflects the seasonal over- and under-supply situations. In the Nordics, over-supply relates to the Spring flooding adding to the hydro reservoirs, and the under-supply situations occur in Winter months. The seasonal pattern in Spain is less clear.

Table B.1: Summary statistics for the changes in consumer surplus

	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
California	2,045	0.31	1.84	−1.23	−0.06	0.23	33.76
Nordic	2,192	0.43	1.83	−2.45	−0.06	0.27	40.71
Spain	2,192	0.07	0.30	−0.99	−0.13	0.23	1.89

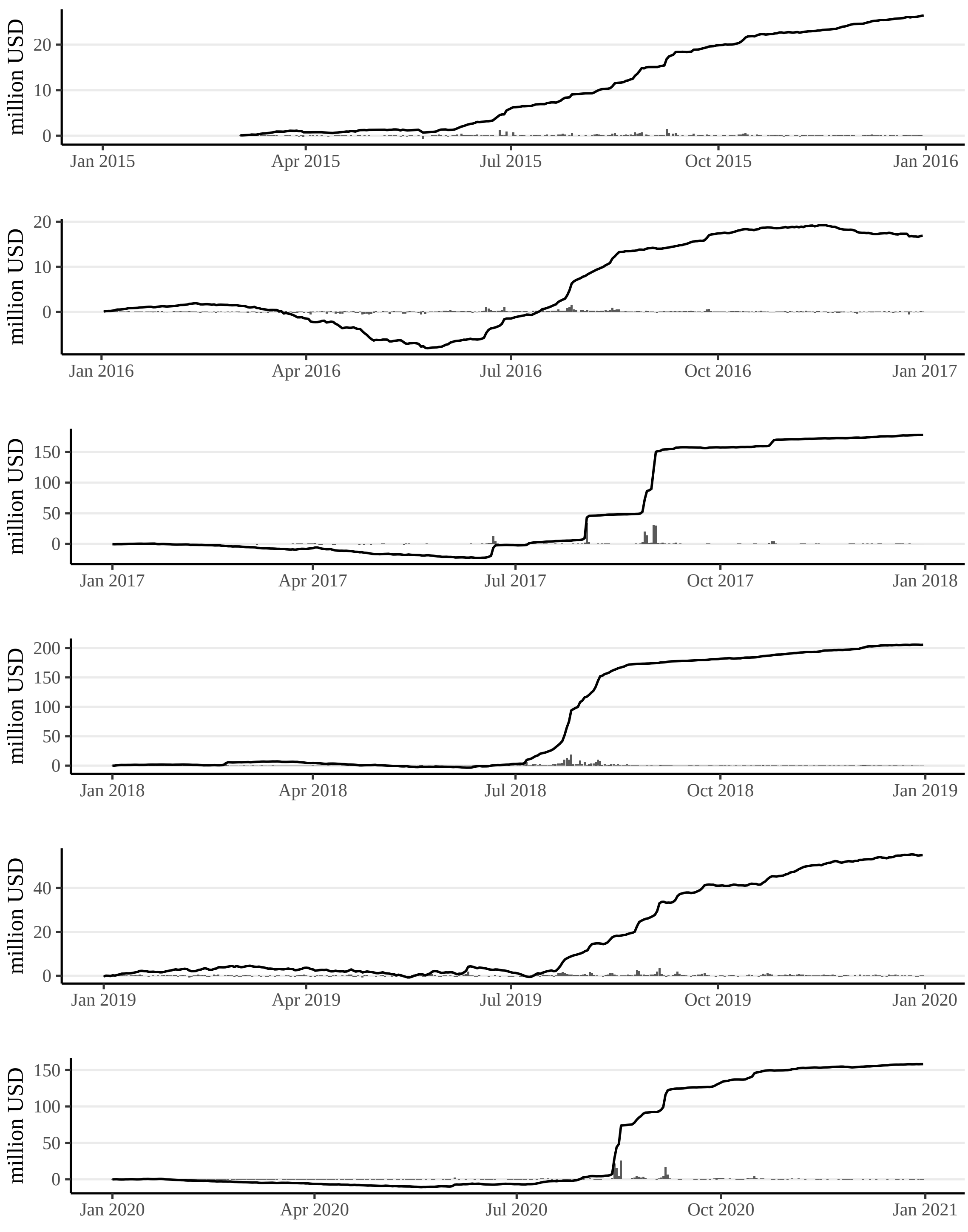
Notes. Daily change in consumer surplus measured in millions of U.S. dollar or euro per day from $1GW$ of capacity for efficiency improvements in the model in Section A.3.2. Data as reported in Table A.1.

Table B.2: Seasonal pattern in consumer surplus change

	California		Nordic		Spain	
	Convexity measure	Consumer surplus change	Convexity measure	Consumer surplus change	Convexity measure	Consumer surplus change
Jan	0.16	0.02	1.34	1.73	-0.39	0.08
Feb	-0.38	-0.005	0.88	1.08	-0.18	0.09
Mar	-0.40	-0.05	0.56	0.66	-0.10	0.08
Apr	-0.61	-0.13	0.15	0.19	-0.05	0.05
May	-0.22	-0.06	-0.30	-0.06	0.09	0.06
Jun	0.89	0.22	-0.20	-0.03	0.31	0.14
Jul	3.64	0.83	-0.12	-0.01	0.02	0.11
Aug	6.53	1.51	0.02	0.07	0.11	0.09
Sep	3.55	0.79	-0.06	0.04	0.10	0.06
Oct	1.95	0.27	0.05	0.12	0.18	0.07
Nov	0.92	0.12	0.77	0.77	-0.18	0.05
Dec	0.52	0.11	0.46	0.59	-0.47	0.01

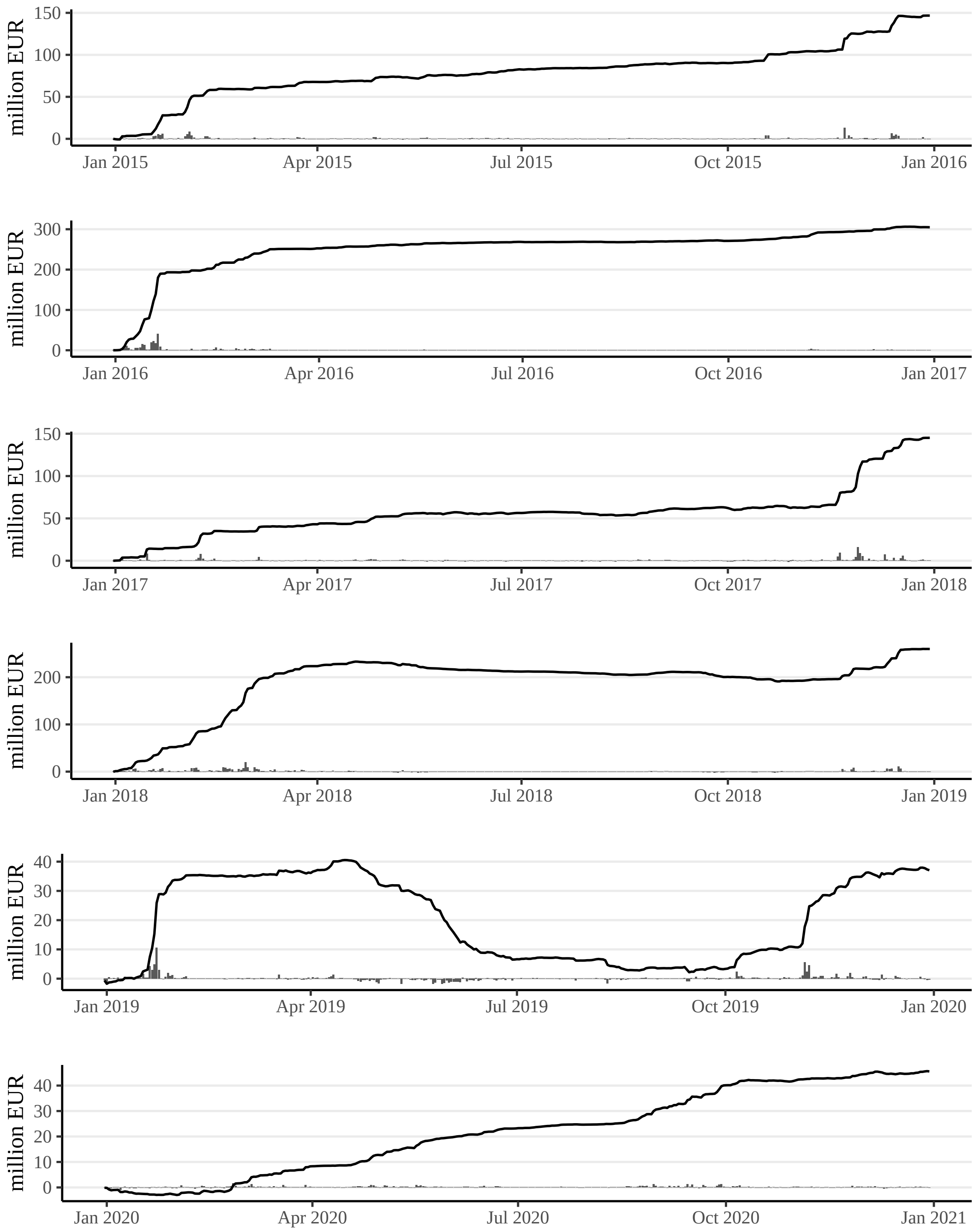
Notes: Monthly means of the daily values of the aggregated excess demand convexity measure and consumer surplus in three different markets. Convexity measure is in U.S. dollar or euro per megawatt hour and consumer surplus change measured in million U.S. dollar or euro. Data as reported in Table A.1.

Figure B.1: Change in consumer surplus in California in 2015–2020



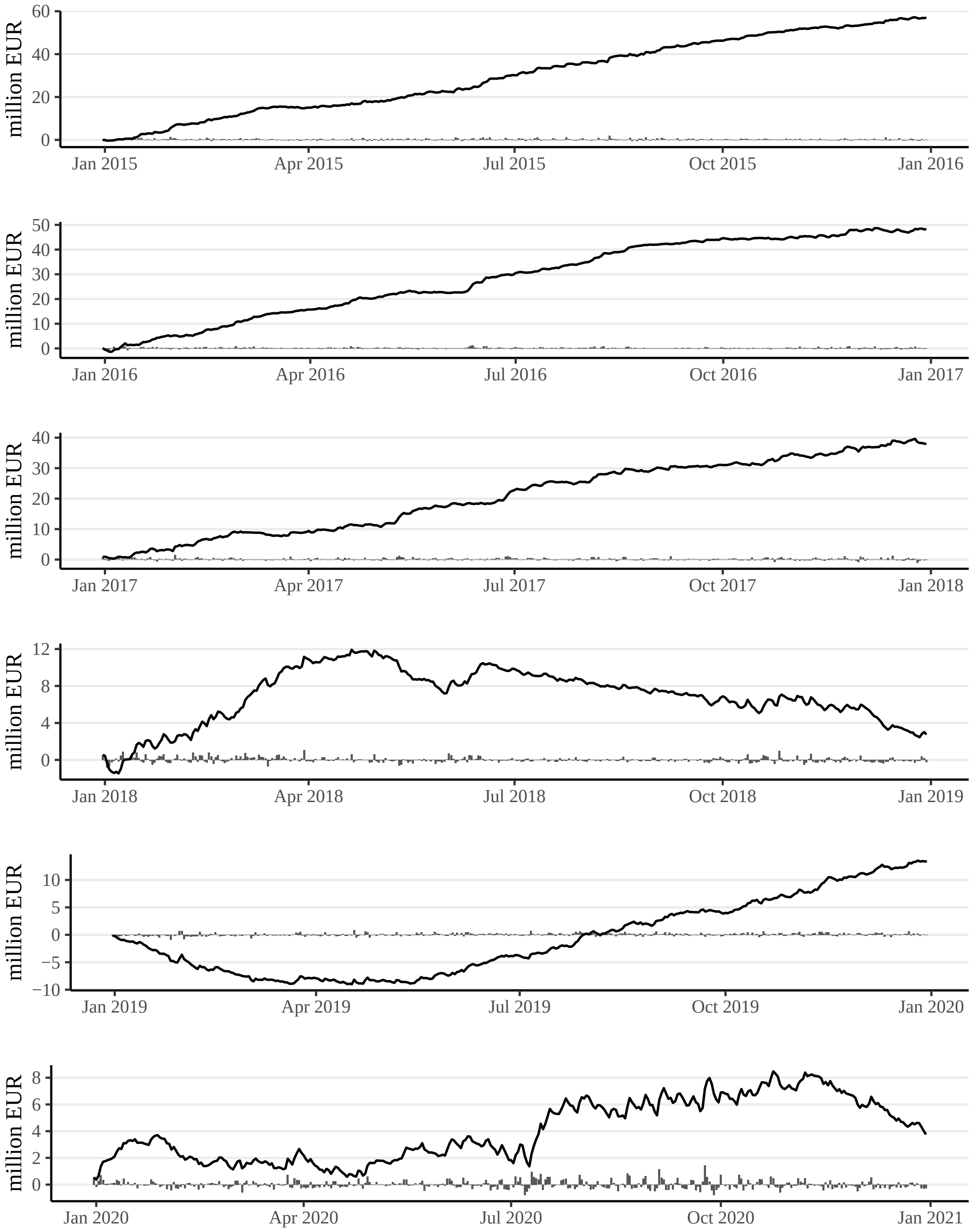
Notes: Changes in consumer surpluses in California. The comparison is between the counterfactual equilibrium with 1 GW trade and the equilibrium without trade. Each bar on the horizontal axis represents the change in surplus over one day (calculated as a sum of the hourly values) and the lines show the cumulative sum of the daily values over one year. Each panel shows the years from 2015 (Top) to 2020 (Bottom).

Figure B.2: Change in consumer surplus in the Nordic market in 2015–2020



Notes: Changes in consumer surpluses in the Nordic market. 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 over one year. Each panel shows the years from 2015 (Top) to 2020 (Bottom).

Figure B.3: Change in consumer surplus in Spain in 2015–2020



Notes: Changes in consumer surpluses in Spain. 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 over one year. Each panel shows the years from 2015 (Top) to 2020 (Bottom).

B.2 Descriptives: covariates used in the regressions

Table B.3 reports the summary statistics for the covariates used in the regressions. The convexity measure gives the convexity (+) or concavity (-) of the daily excess demand curves in euro or dollar per MWh. All covariates are defined in the main text.

Table B.3: Summary statistics of the covariates

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Convexity measure							
California ($/MWh)	2,045	1.43	7.72	−8.95	−0.32	1.21	132.54
Nordic (€/MWh)	2,192	0.29	1.57	−6.44	−0.23	0.41	19.43
Spain (€/MWh)	2,192	−0.04	1.40	−6.04	−0.88	0.78	6.65
Variation of demand							
California (GW)	2,045	4.15	1.70	1.42	2.92	5.14	11.08
Nordic (GW)	2,192	4.04	1.31	0.83	3.05	4.94	7.55
Spain (GW)	2,192	4.04	1.03	1.70	3.24	4.73	7.70
Variation of supply							
California (GW)	2,045	3.66	1.01	1.03	2.94	4.37	6.57
Nordic (GW)	2,192	1.44	0.56	0.19	1.03	1.80	3.39
Spain (GW)	2,192	2.92	0.96	0.81	2.22	3.56	7.07
Correlation between demand and supply							
California	2,045	0.15	0.27	−0.61	−0.02	0.34	0.81
Nordic	2,192	0.80	0.24	−0.76	0.75	0.94	1.00
Spain	2,192	0.71	0.27	−0.69	0.62	0.89	0.99
Pass-through							
California	1,844	0.87	0.05	0.68	0.85	0.91	0.97
Nordic	2,150	0.98	0.03	0.62	0.98	0.99	1.00
Spain	2,051	0.73	0.12	0.28	0.68	0.82	0.96

Notes. All covariates are defined in the main text.

B.3 Annual variation

Table B.4 unpacks the trends underlying the results presented in Table 3 in the main text. Table B.4 shows the results of Table 3 for marginal impacts at $1GW$ efficiency mandate separately for all years. In California, the technology surplus increases over time: the rapid increase in solar power during the time period has increased the value of technologies that counterbalance the increased intermittency. In Spain, the changes in bid curves suggest an increase in the market-level demand response, reducing the technology surplus due to the mandate. In the Nordics, we see no similar systematic trends.

Table B.4: Technology impact: marginal values

	Δ technology surplus			Δ consumer surplus		
Year	California	Nordic	Spain	California	Nordic	Spain
2015	12.5	4.3	19.1	27.8	105.0	56.3
2016	19.8	5.2	14.1	15.8	153.5	34.4
2017	48.0	3.6	16.6	172.3	78.4	24.6
2018	68.0	5.3	15.0	200.4	121.3	6.3
2019	49.5	5.3	11.5	53.5	22.7	13.2
2020	52.5	1.9	9.8	119.9	25.3	9.6

Notes. The marginal value of the new technology and marginal change in consumer surplus at $1GW$ efficiency mandate. All changes in annual mean values measured in units of million U.S. dollar or euro per GW (equal to dollar or euro per kW).

C Robustness

C.1 Correlation of covariates

Table C.1 reports the results from regressing each of the covariates in the main analysis (see Table 2) individually. The only covariate in addition to the convexity measure that explains variation in the consumer surplus is the pass-through measure for the Nordics (column 5, Nordics). We show next that the result follows because pass-through as a variable is badly defined in serious under-supply situations.

Table C.1: Explaining the change in consumer surplus

A. California

Model:	(1)	(2)	(3)	(4)	(5)	(6)
(Intercept)	0.313 (0.041)	-0.010 (0.013)	-1.45 (0.099)	0.889 (0.153)	0.251 (0.046)	5.53 (0.840)
Convexity		0.226 (0.002)				
Variation, Demand			0.425 (0.022)			
Variation, Supply				-0.157 (0.040)		
Correlation					0.422 (0.153)	
Passthrough						-5.93 (0.959)
R^2		0.90050	0.15395	0.00743	0.00371	0.02035
Observations	2,045	2,045	2,045	2,045	2,045	1,844

B. Nordics

Model:	(1)	(2)	(3)	(4)	(5)	(6)
(Intercept)	0.428 (0.039)	0.120 (0.017)	-0.991 (0.123)	-0.983 (0.104)	-0.295 (0.137)	54.5 (0.768)
Convexity		1.06 (0.010)				
Variation, Demand			0.351 (0.029)			
Variation, Supply				0.980 (0.067)		
Correlation					0.909 (0.165)	
Passthrough						-55.1 (0.782)
R^2		0.82786	0.06274	0.08848	0.01372	0.69804
Observations	2,192	2,192	2,192	2,192	2,192	2,150

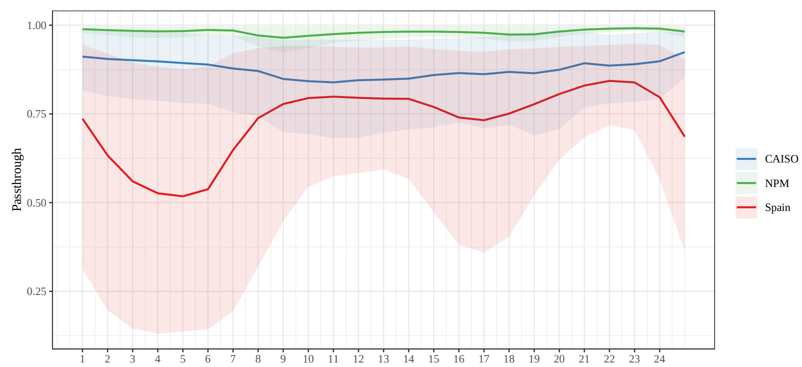
C. Spain

Model:	(1)	(2)	(3)	(4)	(5)	(6)
(Intercept)	0.074 (0.006)	0.081 (0.005)	0.360 (0.025)	0.146 (0.021)	0.149 (0.018)	0.598 (0.040)
Convexity		0.138 (0.004)				
Variation, Demand			-0.071 (0.006)			
Variation, Supply				-0.025 (0.007)		
Correlation					-0.106 (0.024)	
Passthrough						-0.719 (0.054)
R^2		0.40631	0.05778	0.00595	0.00879	0.07923
Observations	2,192	2,192	2,192	2,192	2,192	2,051

Notes. Panels replicate reduced form regression in Table 2 by introducing one covariate at a time. The dependent variable is the change in the daily consumer surplus, measured from the demand side bids before and after the technology experiment. Convexity is Jensen's gap calculated from the daily excess demand. Variation Demand and Variation Supply are standard deviations obtained, together with Correlation, from the daily correlation matrices for quantities from the bid curves. Pass-through is the pass-through rate using the empirical estimates of local elasticities at equilibrium from the bid curves.

First, fig. C.1 shows the underlying hourly data that is used to construct the daily pass-through measure. The pattern in California and the Nordic market is stable over all the hours of the day and variations in the $10\% - 90\%$ band are modest: both markets are characterized by high pass-through, indicating low demand elasticity in normal times. In Spain, the pass-through is lower and more volatile, indicating more elastic response from the demand side.

Figure C.1: Passthrough by the hour and area



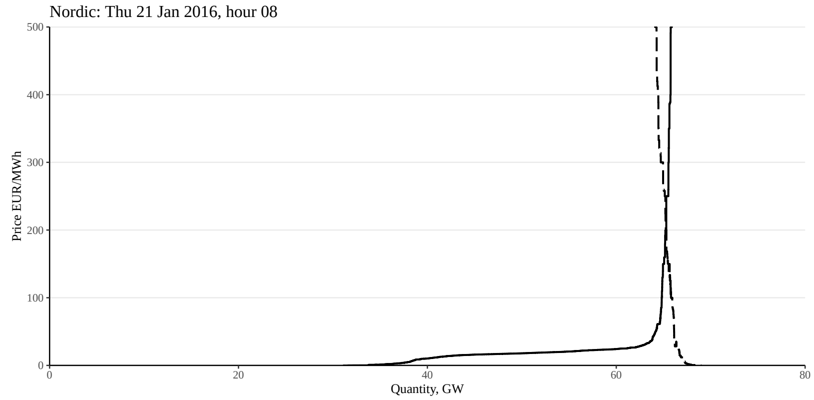
Notes: Means and 10% and 90% percentiles of the hourly pass-throughs by the market for all the data.

Second, the modest variation of the pass-through shown just above is difficult to reconcile with the variable explaining 70% of the changes in consumer surplus in the Nordic market, as in Table C.1. We have scrutinized the occurrences of low pass-through values: they are correlated with serious under-supply situations such as those described in Fig. C.2. The pass-through takes low values in these situations not only because the demand elasticity is high but because the supply becomes close to vertical. As a result, the pass-through measure captures the convexity of supply in quantities. This way it captures the same phenomenon as the convexity of excess demand in such extreme situations.

C.2 Storage application

Our main model for counterfactuals (see Section A.3) poses no limits on trade across hours, other than the capacity limit Y for the exports and imports, and no losses occur if trade takes place. Here we impose more structure on the problem and explicitly model a battery storage with limited capacity and round-trip efficiency losses from the conversion of energy to and from the battery.

Figure C.2: Example of bid curves in the Nordic market when prices are high



Notes: Example of the market primitives during the highest price hour in the Nordic market in our data set. Demand is not more responsive, but high pass-through is explained by the inelastic supply.

Model with storage: We start with the model (4) and maintain the limit on the aggregate trade over the hours of any given day: $\sum_{h \in \mathcal{H}} X_h = 0$. The objective remains

$$\max_{Q^d_{i,h}, Q^s_{j,h}} \sum_{h \in \mathcal{H}} \left[\sum_{i \in \mathcal{D}_h} p_{i,h} Q^d_{i,h} - \sum_{j \in \mathcal{S}_h} p_{j,h} Q^s_{j,h} \right], \tag{5}$$

but now we need to track the chronological order of trade and the losses. The round-trip losses are set to burden the "export" side of the balance equations (i.e., input and output capacities of the battery are different). We divide the excess demand of any hour to positive (imports) and negative (exports) parts, i.e., $X_h = X_h^+ + X_h^-$. The losses are included as a percentage drop in efficiency $1 - \nu$, so that $L_h = (1 - \nu) X_h^-$. Lastly, we constraint the stored energy to stay between zero and a fixed capacity K for any hour $\tau \in \mathcal{H}$. The battery state at the start of the day is alway fixed at 0. The full set of constraints is

$$\begin{aligned}
X_h^+ + X_h^- + L_h = Q_h^d - Q_h^s, \quad \forall h,\\
0 \leq X_h^+ \leq Y \quad \forall h,\\
-Y \leq X_h^- \leq 0 \quad \forall h,\\
L_h = (1 - \nu) X_h^- \quad \forall h,\\
\sum_{h \in \mathcal{H}} X_h^+ + X_h^- = 0\\
0 \leq \sum_{h \in \mathcal{H}_\tau} X_h^+ + X_h^- \leq K \quad \forall \tau \in \mathcal{H},
\end{aligned}$$

here $\mathcal{H}_\tau$ collects the hours until hour τ, $\mathcal{H}_\tau = 1, \ldots, \tau$.

The computations are for a typical battery specification, similar to those in Butters, Dorsey and Gowrisankaran (2021): the round-trip efficiency of the battery is $\nu = 85\%$ and we use 4-hour duration, i.e. $K = 4Y$. The results from running the experiment with varying storage capacities are presented in Table C.2. The results for surpluses for the California mandate level of $1.3GW$ come close to those from our generic technology experiment with lower capacity ($1GW$). For the Nordic market, the consumer surplus impact of the generic mandate arises at the storage capacity closer to $2.5GW$.

Table C.2: Technology impact: storage

Energy	Power	Technology surplus			Consumer surplus		
MWh	MW	California	Nordic	Spain	California	Nordic	Spain
0	0	0	0	0	0	0	2.6
100	25	1.1	0.2	0.5	2.5	5.2	-0.2
1000	250	10.1	1.8	4.8	22.1	37.2	0.6
5200	1300	42.5	4.7	16.1	105.4	116.1	4.6
10000	2500	65.0	4.3	18.6	188.3	163.0	2.7
25000	6250	76.4	0.6	7.4	360.9	214.1	7.6
50000	12500	26.7	0	0.1	513.3	217.6	16.0

Notes. Technology surplus and consumer surplus with varying battery energy and power capacities. Round-trip efficiency of 85% is used throughout. Surplus changes reported in annual mean values in the data period, measured in units of million U.S. dollar or euro per GW (equal to dollar or euro per kW).

Qualitatively the storage specification produces the same results as our main model for California and the Nordics: the technology surplus remains low but the consumer surplus increases in the capacity. The results look drastically different for Spain where consumers benefits are wiped out when stricter constraints are put on the technology. A part of the explanation is given by Fig. C.1: the battery is optimally charged during the night when the demand elasticity is consistently higher, which leads to a rise in average prices, and this together with the technology constraints limits the gains from optimally utilizing the storage in the other hours. In the Nordics, the losses in efficiency reduce technology surplus, but the consumer surplus remains high in the data period; the constrains for the storage do not eliminate its ability to cut the peak prices. Finally, in all markets, sufficiently large increases in the battery storage reduce the technology surplus from the technology; in the Nordics and Spain the whole benefit is eliminated with a $50,000MWh$ battery.