Aggregation of demand-shifting resources in a 'smart' electricity network*

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May 30, 2025

Abstract

In a 'smart' electricity network households' demand-shifting resources can be aggregated to improve efficiency in the electricity market. But aggregation may enable whoever controls resources to exercise market power. This paper establishes a ranking of market structures under imperfect competition. Multiple independent aggregators are more efficient than an integrated distribution system operator (DSO)/aggregator, which is more efficient than an integrated generator/aggregator, which is more efficient than no market for aggregation of demand-shifting resources. The paper also characterizes a regulation that implements the efficient outcome.

Key words: Aggregator, distribution system operator, electricity market, market power, smart grid

JEL codes: H41; L12; L51; L94

*Many thanks to David Andrés-Cerezo, Therése Hindman Persson, Lennart Söder, seminar participants at the Swedish Competition Authority and the Swedish Energy Markets' Inspectorate and conference participants at the 9th Mannheim Conference on Energy and the Environment for comments and discussion. Financial support from the Swedish Energy Agency (2015-002474) is gratefully acknowledged.

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1 Introduction

Electricity production from renewable energy sources has expanded in many jurisdictions over the last two decades. The variability of solar and wind power has increased the value of intertemporal substitution of electricity consumption to reduce the total cost of balancing supply and demand in the electricity market.

At the same time, technological development has enhanced the potential for demand-shifting at the household level. Digital thermostats can adapt the energy used for heating and cooling to short-term changes in the price of electricity. The charging pattern of plug-in electric vehicles can be optimized to minimize user cost. Hot water heaters and solar-plus-storage systems can be used for the same purpose. However, individual households may have weak incentives to apply digital technologies for demand-shifting purposes. They can be on retail contracts that do not enable them to respond to short-term price variability, or maybe the value of using the digital equipment is not worth the cost of installing it.

The untapped demand-shifting potential has created a business opportunity. In a 'smart' electricity network, third parties can manage the electricity consumption of individual households by remote control. So-called *aggregators* can make a profit by optimizing the households' combined demand-shifting resources in the electricity market. For instance, the German company Sonnen offers a contract to house owners with solar-plus-storage equipment. Customers pay a fixed fee for an annual consumption allowance. Sonnen then uses the storage capacity for balancing purposes in the electricity market.[1]

There is increasing policy awareness of the benefits of activating demand-shifting resources. The regulatory framework governing the internal market for electricity in the European Union aims to facilitate implementation of such solutions (EU, 2019). In the U.S., the Federal Energy Regulatory Commission has adopted a reform with a purpose of removing barriers to entry of distributed energy resource aggregation (FERC, 2020).

This paper develops a theoretical framework to analyze the properties of a market for aggregation of demand-shifting resources. The key assumption is that control of aggregation resources may yield market power in the short-term electricity market.[2] How does competition in the market for aggregation affect the efficiency of resource allocation? What are the consequences of vertical integration between system operation of the electricity market and aggregation? What if a generation owner participates in the market for aggregation? What are the properties of efficient regulation? Answers to these questions can be helpful in making informed policy choices regarding the emerging market for aggregation of demand-shifting resources.

2 Related literature

Burger et al. (2017) describe key players and core activities performed in a smart electricity network with aggregation resources. One of those actors is the distribution system operator (DSO)

[1] https://sonnen.de/stromtarife/sonnenflat-home/, May 28, 2025.

[2] See Pollitt and Anaya (2021) for a discussion about the potential for competition in the short-term market.

who has the responsibility for maintaining the balance between consumption and production in the network (EDSO, 2015).[3] The DSO often is the owner of the network. It solves its task by procuring capacity through long-term mechanisms or in a short-term market. Potentially, it can even aggregate demand-shifting resources. Independent aggregators or firms that serve the retail market or own generation capacity may also participate in the market for aggregation.

Burger et al. (2019a,b) emphasize the incentives of a DSO that also controls aggregation resources to distort competition in the aggregation market by restricting access to the distribution network or the short-term market. I show that short-term distortions may persist because of imperfect competition in the market for aggregation, even if the regulatory framework guarantees third-party equal access to the network.

Brown and Sappington (2018, 2019) analyze the incentives for network owners to procure flexibility resources and show how these incentives depend on regulatory policy. Kim et al. (2017) develop a model where multiple system operators own local balancing capacity in an integrated network. They devise a cost-sharing mechanism that ensures efficient resource allocation. The present context considers a single system operator that does not own any capacity. Instead, inefficiencies arise from exercise of market power in the deployment of aggregation resources.

The modeling framework in this paper resembles the Hotelling model of resource extraction which considers the problem of how much of a finite resource to extract today and how much to save for the future. Under imperfect competition the equilibrium in the Hotelling model is found at the point at which the marginal revenue is equalized across periods; see Tangerås and Mauritzen (2018) and the references therein.[4] However, that literature does not compare different market structures.

3 The efficient benchmark

This section develops a two-period model of an electricity market where demand differs across periods. The traditional way of clearing an electricity market is by dispatching sufficient flexible generation in each period. In this model, there is also a second way to accomplish market-clearance. Some of the electricity consumption goes into supplying an energy service to households. A prime example is indoor temperature (heating and cooling). By the laws of thermodynamics, a constant indoor temperature can be achieved by different combinations of electricity consumption in the two periods. The heating system represents a demand-shifting resource by its ability to substitute electricity consumption across periods.

Intertemporal substitution of household consumption reduces total production cost by offsetting the variability in demand. However, full marginal cost equalization is inefficient by an

[3] If imbalances become too severe, then units and grid components will disconnect. This process can develop into a serious system interruption unless contained. A famous example is the Northeast blackout of 2003 that started with a power plant in Ohio shutting down. The failure spread through the system as transmission lines sequentially tripped offline. The ensuing outage affected 10 million people in Ontario and 45 million people in eight U.S. states.

[4] A related literature analyzes strategic interaction between sequential markets by firms with market power, but without considering storage technologies; see, for instance Ito and Reguant (2016) and Rintamäki et al. (2020).

assumption that households have intertemporal preferences over consumption of the energy service. Efficient allocation of the demand-shifting resource therefore equalizes the marginal utility of consumption minus the marginal cost of production across periods.

I show that a perfectly competitive market can implement the efficient outcome if all market participants are exposed to marginal short-term prices. In this section, I also identify a fundamental inefficiency associated with this market design if consumers are passive in the sense that they do not respond to short-term price changes. Under such market incompleteness, electricity consumption in the peak demand period is too high compared to the off-peak demand period.

The model There are two dispatch periods $i = 1, 2$, each featuring exogenous demand for $x_i > 0$ megawatt hours (MWh) electricity that is entirely unresponsive to price changes.[5] It consists of industry and residential consumption minus variable renewable energy generation. I set $x_1 < x_2$, so that period 1 is the *off-peak demand period* and 2 is the *peak demand period*.

A continuum of representative households of measure one use an energy service in amount $\bar{s} > 0$. This service is produced by consuming $s_1 = s \in [0, \bar{s}]$ MWh electricity in period 1 and $s_2 = \bar{s} - s$ MWh in period 2. One can think of the energy service as the production of heat (or cooling) to generate indoor temperature $\bar{s}$.[6] Substitution is imperfect from the viewpoint of the household by the utility function $\tilde{U}(s_1, s_2)$. Let $U(s) = \tilde{U}(s, \bar{s} - s)$ be twice continuously differentiable and concave in s. Assume that an even distribution of electricity consumption, $s = \frac{\bar{s}}{2}$, across both periods maximizes household utility.

A flexible technology is available to cover total demand $q_i = x_i + s_i$ in each period $i = 1, 2$. It is most relevant to think of this technology as thermal generation capacity, but it can also be other flexible consumption. Let the cost function $C(q)$ of supplying q MWh electricity by the same in both perids. The marginal cost function $C'(q)$ is twice continuously differentiable, strictly increasing and strictly convex for all $q > 0$.

The efficient allocation The central planner chooses $s \in [0, \bar{s}]$ to maximize the welfare

$$W(s) = \tilde{U}(s, \bar{s} - s) - C(x_1 + s) - C(x_2 + \bar{s} - s) \tag{1}$$

of electricity consumption and production. Let $s_1^{fb} = s^{fb}$ in period 1 and $s_2^{fb} = \bar{s} - s^{fb}$ in period 2 denote the efficient electricity consumption to supply the energy service. The efficient production of electricity equals $q_i^{fb} = x_i + s_i^{fb}$ in period $i = 1, 2$. I assume an interior optimum,

[5] In the European electricity market, a dispatch period is currently 60 minutes. However, dispatch periods will be shortened to 15 minute intervals in 2025.

[6] Energy storage (e.g. batteries, plug-in electric vehicles) is another relevant example that enables intertemporal substitution. Storage technologies can be incorporated through a slight reformulation of the framework. Consider a battery with $2\bar{s}$ MWh charging capacity. Assume that this battery enters period 1 with a charge of $\bar{s}$ MWh. The battery can then withdraw $s \in [-\bar{s}, \bar{s}]$ from the grid in period 1. Under the assumption that the battery must maintain charging capacity $\bar{s}$ after the end of period 2, it follows that $s_2 = -s$. Such modifications to the model would have no bearing on the results of the paper

$W'(s^{fb}) = 0$, which is then characterized by

$$\frac{\partial \tilde{U}(s_1^{fb}, s_2^{fb})}{\partial s_1} - C'(q_1^{fb}) = \frac{\partial \tilde{U}(s_1^{fb}, s_2^{fb})}{\partial s_2} - C'(q_2^{fb}). \tag{2}$$

The marginal social net benefit of consuming the energy service is equalized across periods. Strict concavity of the welfare function $W(s)$, and $W'(\frac{1}{2}\bar{s}) = C'(x_2 + \frac{1}{2}\bar{s}) - C'(x_1 + \frac{1}{2}\bar{s}) > 0$ imply that the efficient allocation of resources requires the supply of the energy service to consume more electricity in the off-peak than the peak demand period, $s^{fb} > \frac{1}{2}\bar{s}$. The central planner allows some inefficiency in household consumption to reduce the difference in marginal production cost across periods and thereby diminish the total cost of electricity supply.

Observation 1 *Efficient demand shifting implies that more of the electricity required to produce the energy service is consumed in the off-peak compared to the peak demand period, $s^{fb} > \frac{1}{2}\bar{s}$.*

A competitive short-term market in which all market participants are exposed to marginal short-term prices implements the efficient outcome. The production of electricity is efficient if the marginal price of electricity is $p_i^{fb} = C'(q_i^{fb})$ in period $i = 1, 2$, and electricity consumption to produce the household energy service is efficient. Household maximization of $U(s) - p_1^{fb}s - p_2^{fb}(\bar{s} - s)$ indeed yields $s = s^{fb}$.

Short-term market incompleteness There are several reasons why efficient consumption would be infeasible even in a competitive electricity market. Most often, consumers remain unexposed to marginal short-term prices, for instance because they pay a single retail price that is a function of those prices. To account for such market incompleteness, I assume that households pay the average short-term price $\frac{1}{2}(p_1 + p_2)$ for consumption of the energy service. In this case, households cannot benefit from deviating from their most-preferred consumption $\frac{1}{2}\bar{s}$ because the cost of electricity is $\frac{1}{2}(p_1 + p_2)\bar{s}$ regardless of s.

Passive consumers imply that the market equilibrium has too little production in the off-peak demand period, $x_1 + \frac{1}{2}\bar{s} < q_1^{fb}$, and excessive production in the peak demand period, $x_2 + \frac{1}{2}\bar{s} > q_2^{fb}$. This inefficiency opens up for solutions that aim to increase the sensitivity to price signals other than through exposure of households to marginal short-term prices. This paper considers a market for aggregation of demand-shifting resources.

Another reason why a decentralized solution might be inefficient is because households might have to invest in equipment to be able to respond to those prices. The perceived household cost savings associated with short-term optimization could be small relative to the investment cost. I discuss the implications of such costs below.

4 A market for aggregation of demand-shifting resources

Assume that centralized dispatch or a fully decentralized market with marginal short-term price exposure for consumers are both infeasible. Instead, a DSO is responsible for clearing production and consumption in each period. The DSO has no production capacity of its own and therefore has to ensure that generation owners supply the required power to match production with consumption in every period.

The DSO organizes trade in a short-term market. Flexible generation is supplied at marginal cost. All dispatched electricity within each period receives a compensation equal to the marginal cost of the most expensive production cleared in the market. Hence, $P(q_i) = C'(q_i)$ represents the inverse supply function of electricity generation q_i in period i. The assumption that electricity is supplied by generation owners at marginal cost allows to isolate the effects of imperfect competition in the market for demand shifting resources on the efficiency of the short-term electricity market.[7]

Market structures Figure 1 displays potential structures of the electricity market. There are three generation owners, $\{G_1, G_2, G_3\}$, three retailers, $\{R_1, R_2, R_3\}$, and up to three aggregators $\{A_1, A_2, A_3\}$. Each generator submits an offer to sell electricity (its marginal cost curve) to the DSO. Each retailer and each aggregator submits its inelastic demand for electricity to the DSO. All these actions are marked by arrows in the figure. Based on the supply and demand bids, the DSO chooses the price of electricity that clears the market. I evaluate four market structures.

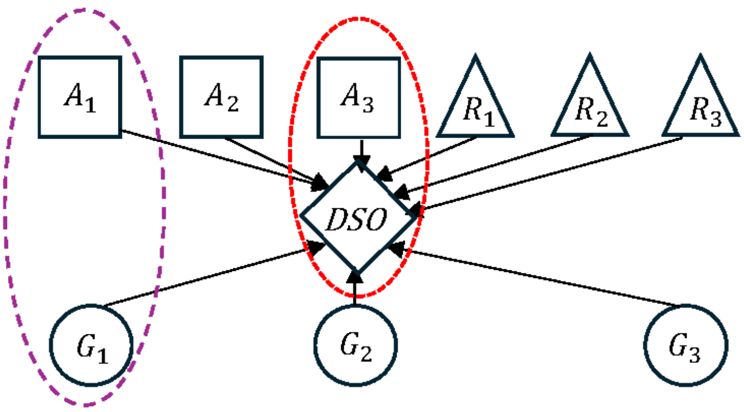

Figure 1: Market structures in the electricity market

Section 4.1 starts the analysis by considering a vertically integrated DSO with a monopoly in the market for aggregation of demand-shifting resources. This is the market structure identified by the dotted red oval in Figure 1, but where A_1 and A_2 are eliminated from the figure. A market structure in which the DSO is active in the aggregator business is policy relevant. EU regulation permits parent companies to own business entities that operate distribution networks as well as entities that participate in the deregulated parts of the electricity market, provided those entities are independent in terms of "legal form, organization and decision-making" (Article 35 of EU, 2019).[8]

[7] This is chiefly a simplifying assumption. Most of the results carry over to a setting with market power in the supply of thermal electricity. The analysis is available on request.

[8] The rules concerning vertical unbundling of DSOs are not mandatory for vertically integrated undertakings that serve fewer than 100 000 connected customers (Article 35 of EU, 2019).

In the analysis in Section 4.2, the DSO does not participate in the market for aggregation. Instead, independent aggregators compete for demand-shifting resources. This situation is illustrated in Figure 1 by a market structure without the red dotted (or the purple bracketed) oval. The section also discusses integration between retail operations and aggregation. Both types of aggregators are common in the European electricity market.

In the mixed market structure analyzed in Section 4.3, an integrated DSO/aggregator competes alongside independent aggregators in the market for aggregation. This hypothetical situation is illustrated in Figure 1 by the red dotted oval, and where all three aggregators participate in the market. The analysis in the section emphasizes potential strategies the DSO can utilize to foreclose competitors A_1 and A_2.

The analysis in Section 4.4 considers vertical integration between a generation owner and an aggregator. This constellation is common in the European electricity market. The analysis assumes that the DSO does not participate in the market for aggregation. This situation is illustrated by the purple dashed oval in Figure 1.

4.1 Monopoly integrated DSO/aggregator

Demand-shifting operates as follows when a parent company owns the DSO entity and an aggregator entity with a monopoly in the market for aggregation. The aggregator entity offers to supply the energy service for a fixed fee t. Assuming that households accept the offer (more on this below), the aggregator purchases electricity s in period 1 and $\bar{s} - s$ in period 2 to supply the energy service. It pays $p_1 s + p_2(\bar{s} - s)$ for this electricity. The DSO entity purchases residual demand x_1 and x_2 from generation owners at cost $p_1 x_1 + p_2 x_2$.[9] The DSO's cost of procuring power to maintain system balance is often considered unavoidable and therefore added in full to the DSO's revenue cap.

The joint profit of the monopoly integrated DSO/aggregator equals

$$F + t - P(x_1 + s)s - P(x_2 + \bar{s} - s)(\bar{s} - s)$$

under complete cost pass-through. F is the revenue cap net of purchases in the short-term market.[10] Electricity consumption s matters for profit even if the DSO entity is regulated because the unregulated aggregator entity is residual claimant to its associated cost savings. The aggregator faces the inverse supply function $P(q_i)$ in the short-term market in period i and therefore has the possibility to exercise market power.

[9] Households typically not only consume s and $\bar{s} - s$ in the two periods, but also x_1 and x_2. Aggregators are only viable if the electricity that goes into producing the energy service can be metered separately from the other household consumption. Such granular metering is a prerequisite for demand-shifting via third-party aggregators.

[10] There is an alternative way to derive this profit expression. Assume that only the DSO contracts with the owners of dispatchable generation capacity for electricity, whereas the aggregator purchases electricity from the DSO at cost $P(q_1)s + P(q_2)(\bar{s} - s)$. The DSO's net cost of purchasing electricity then equals

$$P(q_1)q_1 + P(q_2)q_2 - P(q_1)s - P(q_2)(\bar{s} - s) = P(q_1)x_1 + P(q_2)x_2,$$

which is passed onto consumers. Summing up aggregator and DSO profit yields the profit expression in the main text.

The fee t must be sufficiently low for consumers to accept the offer by the aggregator. A household derives net utility $U(s) - t$ if it accepts the contract proposal and the aggregator supplies the energy service by consuming $s \in [0, \bar{s}]$ in period 1. The value of the outside option equals $U(\frac{1}{2}\bar{s}) - \frac{1}{2}(p_1 + p_2)\bar{s}$ by the assumption that the household pays the average price $\frac{1}{2}(p_1 + p_2)$ for all its consumption by refusing the contract proposal and consumes $\frac{1}{2}\bar{s}$ in every period to produce the energy service. By implication, the maximal tariff the aggregator can charge and still ensure participation is

$$t = \tfrac{1}{2}(p_1 + p_2)\bar{s} - [U(\tfrac{1}{2}\bar{s}) - U(s)].$$

Under this contract, the household pays the same for its electricity consumption as in the outside option minus a discount which compensates it for the inconvenience $U(\frac{1}{2}\bar{s}) - U(s)$ of suboptimal (from the household's viewpoint) energy consumption. A marginal change in s affects the value of the outside option through the effect on the short-term prices and thereby the tariff t required to satisfy the household's participation constraint.

Substituting the fixed fee t into the above profit expression yields the profit of the monopoly integrated DSO/aggregator

$$\Pi(s) = U(s) - U(\tfrac{1}{2}\bar{s}) + [P(x_2 + \bar{s} - s) - P(x_1 + s)](s - \tfrac{1}{2}\bar{s}) \tag{3}$$

as a function of s, net of the regulated revenue F which does not play any role in this analysis. The integrated DSO/aggregator effectively buys the energy service in the short-term market at cost $p_1 s + p_2(\bar{s} - s)$ and earns the revenue $\frac{1}{2}(p_1 + p_2)\bar{s}$ by selling it to the household.[11] The associated profit is the second expression in (3).

The marginal profit of increasing electricity consumption in the first period equals:

$$\Pi'(s) = \underbrace{U'(s) + P(x_2 + \bar{s} - s) - P(x_1 + s)}_{W'(s)} - [P'(x_1 + s) + P'(x_2 + \bar{s} - s)](s - \tfrac{1}{2}\bar{s}). \tag{4}$$

The allocation of resources is distorted by the exercise of market power in the short-term market, identified by the second term in (4). Let s^{DSO} be the equilibrium quantity of electricity consumed by the DSO/aggregator in period 1 to supply the energy service to households.

Proposition 1 *A monopoly integrated DSO/aggregator consumes too little electricity in the off-peak demand period to supply the household energy service, but electricity consumption is still larger in the off-peak than the peak demand period* [$\frac{1}{2}\bar{s} < s^{DSO} < s^{fb}$].

Proof: The marginal profit $\Pi'(s)$ is strictly positive for all $s \leq \frac{1}{2}\bar{s} < s^{fb}$ and strictly negative for all $s \geq s^{fb} > \frac{1}{2}\bar{s}$ by strict concavity of $W(s)$. Hence, $\Pi(s)$ is maximized for some $s^{DSO} \in (\frac{1}{2}\bar{s}, s^{fb})$.■

[11] This is essentially the contract offered by the firm Sonnen described in the Introduction.

Solving the first-order condition $\Pi'(s^{DSO}) = 0$ yields the equilibrium characterization

$$\frac{\partial \tilde{U}(s_1^{DSO}, s_2^{DSO})}{\partial s_1} - p_1^{DSO} - P'(q_1^{DSO})(s_1^{DSO} - \tfrac{1}{2}\bar{s}) = \frac{\partial \tilde{U}(s_1^{DSO}, s_2^{DSO})}{\partial s_2} - p_2^{DSO} + P'(q_2^{DSO})(\tfrac{1}{2}\bar{s} - s_2^{DSO}). \tag{5}$$

where equilibrium production of electricity is equal to $q_1^{DSO} = x_1 + s^{DSO}$ in period 1 and $q_2^{DSO} = x_2 + \bar{s} - s^{DSO}$ in period 2. The equilibrium price is $p_i^{DSO} = P(q_i^{DSO})$ in period $i = 1, 2$. The DSO is a net buyer of electricity in period 1 in the sense that $s_1^{DSO} = s^{DSO} > \frac{1}{2}\bar{s}$. By implication, it has an incentive to shift demand from period 1 to period 2 to reduce the price of electricity in period 1. This anti-competitive effect is identified by the third term on the left-hand side of equilibrium expression (5).

The DSO is a net seller of electricity in period 2, $s_2^{DSO} = \bar{s} - s^{DSO} < \frac{1}{2}\bar{s}$. It then has an incentive to shift demand to period 2 from period 1 to increase the price of electricity in period 2. This anti-competitive effect is identified by the third term on the right-hand side of (5).

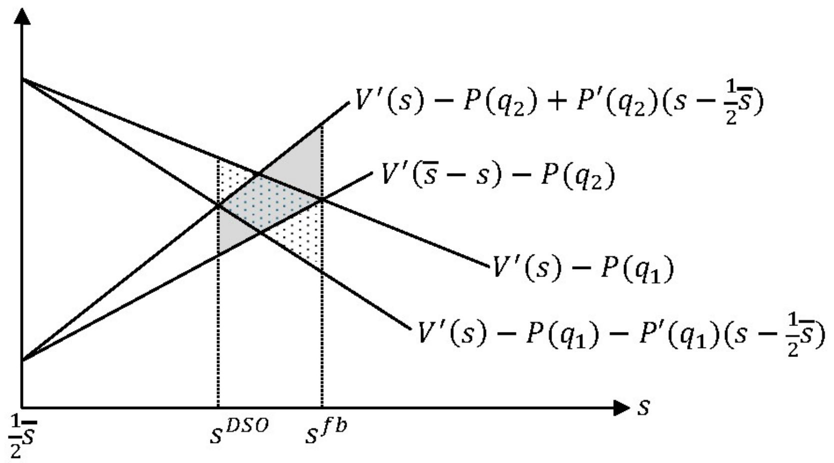

Figure 2: Monopoly DSO

Exercise of market power is illustrated in Figure 2. The vertical axis measures the marginal private and social benefits in the two respective periods as a function of electricity consumption s in period 1, under the simplifying assumption that $U(s) = V(s) + V(\bar{s} - s)$. At $s = \frac{1}{2}\bar{s}$, the marginal social cost $P(x_1 + \frac{1}{2}\bar{s})$ of increasing electricity consumption in period 1 is smaller than the marginal social benefit $P(x_2 + \frac{1}{2}\bar{s})$ of reducing it in period 2 because the marginal production cost is larger in the peak than the off-peak demand period. This relationship holds until the point s^{fb} at which consumption is efficient.

Starting at s^{fb}, the marginal net profit of reducing consumption in period 1 and increasing it in period 2 is positive because the monopoly gains from a lower price in period 1 and a higher price in period 2. The optimum is identified by $s = s^{DSO}$ in figure where the marginal profit of distorting consumption is the same in both periods. The aggregator's equilibrium gain from exercising market power in period 1 is measured by the dotted area in Figure 2, whereas the gain from exercising market power in period 2 is measured by the grey area.

Consumers benefit from aggregation despite the exercise of market power and the nonlinear tariff used by the aggregator to maximize rent extraction. The reason is that aggregation reduces the electricity cost from $\frac{1}{2}[P(x_1 + \frac{1}{2}\bar{s}) + P(x_2 + \frac{1}{2}\bar{s})]\bar{s}$ to $\frac{1}{2}[P(x_1 + s^{DSO}) + P(x_2 + \bar{s} - s^{DSO})]\bar{s}$.

The market for demand-shifting is inefficient despite the aggregator's nonlinear contract with consumers. The distortion occurs by the assumption that the aggregator purchases its electricity at a linear price, which generates an incentive to exercise market power. This incentive would vanish if the aggregator signed nonlinear contracts also with producers. Writing nonlinear contracts with all parties could be infeasible because of contracting costs. Modifications to the aggregation contract signed with households can improve efficiency in that case.

The above contract is *contingent* because the transfer t depends on the realized demand (x_1, x_2) and s. It protects the household from disutility of aggregation by meeting the household's ex post participation constraint. By doing so, it generates an inefficiency because the aggregator holds back first period electricity consumption to reduce compensation to the household for its marginal loss $U'(s)$ in utility.

Consider an aggregation contract where the tariff t renders the household indifferent in expectation between aggregation and an average price contract. In a contract that satisfies the household's ex ante participation constraint, the transfer t is sunk when aggregation occurs. The aggregator then does not have to compensate the household's marginal disutility $U'(s)$ and therefore increases electricity consumption in the off-peak demand period. An aggregation contract that meets the household's ex ante participation constraint therefore has efficiency benefits compared to one that meets its ex-post participation constraint. However, the former exposes the household to larger variation in utility.

An intermediary contract which guarantees the household a minimal utility in every state of the world constitutes a compromise between efficiency and protection of households and could be interesting to explore.

4.2 Independent aggregators

The DSO operates a short-term electricity market to clear demand x_1 and x_2. By complete cost pass-through, it does not have any stake in the market nor does it have any incentive to behave strategically.[12] The market for aggregation of demand-shifting resources consists of $A \geq 1$ *independent aggregators* whose only business is to supply the energy service to households.

Household i receives random utility $\rho v_a + \varepsilon_{ia}$ from purchasing the energy service from aggregator $a \in \{1, ..., A\}$. In the utility expression, $v_a = U(s_a) - t_a$ is the direct utility of consuming aggregator a's energy service if the aggregator consumes s_a in period 1 and charges t_a for its service, and ε_{ia} measures household i's idiosyncratic preference for purchasing the energy service from aggregator a. Each household i draws ε_{ia} from an extreme value distribution with location

[12] A stand-alone DSO also has no incentive to ensure efficient market clearance under a regulatory regime with full cost-pass through. On the contrary, the DSO has a strict incentive *not* to implement efficient solutions if such implementation creates non-monetary costs that the DSO cannot pass onto consumers (Kim et al., 2017). I leave this issue aside.

parameter 0 and scale parameter 1.

The market share of aggregator a equals

$$L_a = \frac{\exp\{\rho v_a\}}{\sum_{a'} \exp\{\rho v_{a'}\}}$$

see, for instance, Besanko et al. (1998). The parameter ρ is a measure of the degree of horizontal differentiation. The larger is ρ, the more important is the direct utility v_a for the choice of aggregator. Aggregator a purchases $L_a s_a$ in the short-term market in period 1 and the remaining $L_a(\bar{s} - s_a)$ in period 2 to supply the energy service to its customers. The measure $s = \sum_{a=1}^{A} L_a s_a$ represents the total demand for electricity in period 1 aggregated across all aggregators. Their corresponding demand in period 2 equals $\bar{s} - s$.

I impose in this subsection a bounded elasticity assumption

$$\frac{C'''(x_i + s_i)}{C''(x_i + s_i)} x_i < 4, \ \forall s_i \in [0, \bar{s}], \ i = 1, 2 \tag{6}$$

on the cost function to ensure that the aggregator profit function is strictly quasi-concave in s_a. It states that the convexity of the marginal production cost cannot increase too fast.[13]

The profit of aggregator a equals

$$L_a[t_a - P(x_1 + s)s_a - P(x_2 + \bar{s} - s)(\bar{s} - s_a)].$$

To be able to compete, this aggregator must offer a contract that is attractive relative to the other aggregators, but also to an outside option in which the household does not use any aggregation service at all. This outside option has the same value $U(\frac{1}{2}\bar{s}) - \frac{1}{2}(p_1 + p_2)\bar{s}$ as in the previous subsection. The aggregator meets this participation constraint by charging a fixed fee equal to

$$t_a = \tfrac{1}{2}(p_1 + p_2)\bar{s} - [U(\tfrac{1}{2}\bar{s}) - U(s_a)] - b_a, \ b_a \geq 0.$$

The value to the household of selecting the contract offered by aggregator a equals $v_a = U(\frac{1}{2}\bar{s}) - \frac{1}{2}(p_1 + p_2)\bar{s} + b_a$. The variable b_a is an incremental benefit which aggregator a chooses endogenously to affect its market share.[14]

Inserting t_a into the above profit function returns aggregator a's profit $L_a[\Pi^A(s_a) - b_a]$, where

$$\Pi^A(s_a) = U(s_a) - U(\tfrac{1}{2}\bar{s}) + [P(x_2 + \bar{s} - s) - P(x_1 + s)](s_a - \tfrac{1}{2}\bar{s}) \tag{7}$$

is the profit per subscriber gross of b_a. The marginal profit

$$\frac{\partial \Pi^A}{\partial s_a} = U'(s_a) + P(x_2 + \bar{s} - s) - P(x_1 + s) - L_a[P'(x_1 + s) + P'(x_2 + \bar{s} - s)](s_a - \tfrac{1}{2}\bar{s})$$

of increasing first-period energy consumption depends of the aggregator's market share. In

[13] An example of a cost function that meets all these requirements is $C(q) = \psi q^{2+\sigma}$, $\psi > 0$, $\sigma \in [0, 4)$.

[14] The utility expression $U(\frac{1}{2}\bar{s}) - \frac{1}{2}(p_1 + p_2)\bar{s}$ is the same for all aggregators, so I can write market share $L_a = \frac{\exp\{\rho b_a\}}{\sum_{a'} \exp\{\rho b_{a'}\}}$

particular, the market power benefits of distorting energy demand is smaller when the aggregator has a smaller market share.

The marginal profit of attracting households through an increase in b_a equals

$$\frac{\partial L^a}{\partial b_a}(\Pi^A(s_a) - b_a) - L^a[1 + (P'(q_1) + P'(q_2))(s_a - \tfrac{1}{2}\bar{s}) \sum_{a'=1}^{A} s_{a'} \frac{\partial L_{a'}}{\partial b_a}]. \tag{8}$$

The first part of this expression is the marginal benefit of having a larger market share. The first term inside the brackets is the direct loss associated with a reduction in the fee t_a. A second and indirect term occurs by the fact that the demand for energy services in the two periods changes when the market shares of the aggregators change (the proof is in Appendix A.1):

Proposition 2 *In symmetric equilibrium, A independent aggregators consume more electricity in the off-peak demand period than the monopoly integrated DSO/aggregator to supply the energy service ($s^A \geq s^{DSO}$ with strict inequality if and only if $A \geq 2$). Still, electricity consumption in the off-peak demand period is inefficiently low ($s^A < s^{fb}$ for any A). A unique symmetric equilibrium exists if horizontal differentiation ρ across aggregators is sufficiently large.*

Solving the first-order condition $\partial\Pi^A/\partial s_a = 0$ for a symmetric equilibrium yields

$$\frac{\partial\tilde{U}(s_1^A, s_2^A)}{\partial s_1} - p_1^A - \frac{1}{A}P'(q_1^A)(s_1^A - \tfrac{1}{2}\bar{s}) = \frac{\partial\tilde{U}(s_1^A, s_2^A)}{\partial s_2} - p_2^A + \frac{1}{A}P'(q_2^A)(\tfrac{1}{2}\bar{s} - s_2^A),$$

where $q_1^A = x_1 + s^A$ measures the equilibrium electricity production in period 1 and $q_2^A = x_2 + \bar{s} - s^A$ the corresponding production in period 2. The equilibrium price is $p_i^A = P(q_i^A)$ in period $i = 1, 2$. The incentive of aggregators to exercise market power by reducing the price of electricity in the off-peak demand period and increasing it in the peak-demand period is muted by the fact that each individual aggregator only internalizes a fraction $1/A$ of the total market power benefits.

Setting the marginal profit (8) to zero, using $\partial L_a/\partial v_a = \rho L_a(1-L_a)$, and imposing symmetry across aggregators, yields the equilibrium discount

$$b^A = \max\{\Pi^A(s^A) - \frac{1}{\rho}\frac{A}{A-1}; 0\} \tag{9}$$

on the aggregator tariffs. The degree ρ of horizontal differentiation affects the distribution of rent between households and aggregators by its effect on b^A, but has no bearing on the efficiency of competition in the market for demand shifting resources in symmetric equilibrium.

Integrated retailers/aggregators Results extend to the case of A integrated retailers and aggregators. Assume that measure one of all households have installed smart grid technologies whereas measure β have not and are passive in the sense that they consume $\frac{1}{2}\bar{s}$ in each period. A passive consumer who is a customer at retailer/aggregator a pays $r_a + \frac{1}{2}(p_1 + p_2)\bar{s}$, whereas a consumer on the aggregator contract pays

$$t_a = U(s_a) - U(\frac{\bar{s}}{2}) + \frac{1}{2}(p_1 + p_2)\bar{s} + r_a - b_a,\ b_a \geq 0,$$

where b_a ensures incentive compatibility of the aggregator contract over the passive retail contract (a passive consumer does not have the possibility to choose an aggregator contract).

The profit of the integrated retailer/aggregator a can be written as

$$L_a[\Pi^A(s_a) - b_a + r_a] + \beta \tilde{L}_a r_a,$$

In this expression,

$$L_a = \frac{\exp\{\rho(b_a - r_a)\}}{\sum_{a'} \exp\{\rho(b_{a'} - r_{a'})\}},\ \tilde{L}_a = \frac{\exp\{-\rho r_a\}}{\sum_{a'} \exp\{-\rho r_{a'}\}}$$

measures a's market share in each of the two consumer segments. The analysis is similar to A independent aggregators, so that Proposition 2 holds. The equilibrium retail tariffs (b_a, r_a) are different, but they have no effect on the short-term market efficiency in symmetric equilibrium.

Aggregation costs Aggregation requires digital technology for external management of household electricity consumption. The costs of such technology may limit competition in the aggregator market. Assume that aggregation requires a fixed investment f for each participating household. The total profit of aggregator a then equals $L_a(\Pi^A(s_a) - b_a - f)$. The fixed cost f does not affect electricity demand in the short-term market, but the equilibrium discount is adjusted accordingly, $b^A = \max\{\Pi^A(s^A) - \frac{1}{\rho}\frac{A}{A-1} - f; 0\}$. The discount is zero if the technology cost is sufficiently large, in which case aggregator profit becomes $\frac{1}{A}(\Pi^A(s^A) - f)$.

I show in Appendix A.1 that aggregator profit $\Pi^A(s^A)$ decreases when competition, measured by A, becomes more intense. Hence, the zero profit condition $\Pi^A(s^A) = f$ endogenously determines $A(f)$. The larger is the fixed cost, the fewer aggregators can profitably enter the market for demand-shifting resources.

4.3 Mixed market structure

This section extends the integrated DSO/aggregator analysis of Section 4.1 from a monopoly in the market for aggregation to an oligopoly in which $A-1 \geq 1$ additional independent aggregators compete for household consumers.

A classical concern when a vertically integrated firm controls access to an essential facility, the distribution network in this case, is that the integrated firm can sustain monopoly power in the downstream market by denying other firms access to the facility (Rey and Tirole, 2007). Regulatory policies mandating network owners to grant competitors non-discriminatory access to the network are standard in many electricity markets to prevent foreclosure.[15]

[15] For instance, Article 31 of EU (2019) states that "the distribution system operator shall not discriminate between system users or classes of system users, particularly in favour of its related undertakings."

A non-discrimination policy alone may be insufficient to ensure competition if the network owner can squeeze competitors in other ways than through direct foreclosure. This problem is obvious in the hypothetical case where aggregators pay the cost of their electricity consumption directly to the DSO who in turn contracts with owners of flexible generation capacity for electricity. The DSO then can drive all aggregators out of the market by overcharging them (including the own entity) the same amount for the cost of electricity.

A solution to the problem of foreclosure through a tariff squeeze is a short-term market which enables aggregators to bypass the DSO by purchasing electricity directly from generation owners. This is the European market design. If the short-term market is complete, in the sense that the independent aggregators face competitive marginal prices in each period, then the outcome under a mixed market structure is the same as one with A independent aggregators. But system operation has features which suggest that short-term markets are incomplete. This incompleteness offers the DSO an effective tool for discrimination, as we shall see. Integrated DSO/aggregators therefore need to be closely scrutinized to avoid discriminating behavior.

Sudden system changes may require fast responses that are impossible to decentralize to a pricing mechanism. Participants in actual short-term markets commit their capacity an entire dispatch period. The system operator dispatches this capacity to balance production and consumption within the dispatch period. Active system operation provides a strategic advantage which an integrated DSO/aggregator can use to seriously distort the market.

I adapt the current model by assuming that one dispatch period consists of two time slots, 1 and 2. Each aggregator commits to purchasing electricity amounting to its total electricity demand during the dispatch period. Generation owners commit to the inverse supply function $C'(q)$ for the dispatch period. The DSO allocates total aggregator demand to each of the two time slots, 1 and 2.[16]

The integrated DSO/aggregator with market share L has profit

$$F + L[t - P(x_1 + s)z - P(x_2 + \bar{s} - s)(\bar{s} - z)]$$

depending on the electricity consumption Lz and $L(\bar{s} - z)$ by its integrated aggregator entity in the off-peak and the peak demand period, respectively. In this expression, $s = Lz + (1-L)y$ is the total electricity consumption in the first time slot, and $\bar{s} - s$ is the total electricity consumption in the second time slot to supply the energy service, where $(1 - L)y$ and $(1 - L)(\bar{s} - y)$ measure the electricity consumption by the independent aggregators in each respective time slot.

I consider the same type of nonlinear contracts by aggregators as in the previous sections, so that the integrated DSO/aggregator has profit $F + L[\Pi^M(z, y) - b]$, where

$$\Pi^M(z, y) = U(z) - U(\tfrac{1}{2}\bar{s}) + [P(x_2 + \bar{s} - s) - P(x_1 + s)](z - \tfrac{1}{2}\bar{s}) \tag{10}$$

is its net profit in the aggregator market.

Aggregators compete for market shares in the first stage, and then submit their total electric-

[16] To simplify proofs, I assume in this section that $U(s)$ has non-negative third derivative.

ity demand to the DSO. In the second stage, the DSO allocates each aggregator's total demand across the two periods. Aggregators then pay the total cost of their electricity consumption. I solve the model by backward induction.

In the second stage, the integrated DSO/aggregator maximizes $\Pi^M(z, y)$ over $(z, y) \in [0, \bar{s}]^2$. Exercise of market power by aggregators in the short-time market implies shifting demand from the off-peak to the peak demand period to reduce price in the former period and increase it in the latter. A DSO/aggregator that allocates the demand of all aggregators can accomplish such demand-shifting in a very profitable way by maximizing the consumption of the *competing* aggregators in the peak demand period. It then allocates the consumption of its own aggregator entity optimally (the proof is in Appendix A.2):

Lemma 1 *Consider a mixed market structure in which an integrated DSO/aggregator and $A-1$ independent aggregators compete in the market for aggregation of demand-shifting resources. Assume that the DSO allocates total aggregator demand for electricity across the two time slots. The DSO allocates all demand of the independent aggregators to the time slot with peak demand [$y^M = 0$ for all $L \in (0, 1)$].*

Lemma 1 characterizes allocations in the short-term market when markets shares in the market for aggregation are given. Consider now the first stage in which aggregators compete for market shares. Aggregator a with market share $L_a > 0$ has profit $L_a(\pi_a^M - b_a)$, where

$$\pi_a^M = U(y_a^M) - U(\tfrac{1}{2}\bar{s}) + (p_2^M - p_1^M)(y_a^M - \tfrac{1}{2}\bar{s})$$

is its net profit in the market for demand-shifting resources, $p_1^M = P(x_1 + s^M)$ is the short-term price in period 1, and $p_2^M = P(x_2 + \bar{s} - s^M) > p_1^M$ is the price in period 2. This profit is negative by $y_a^M = 0$.

The DSO's incentive to allocate the electricity consumption of independent aggregators to the peak demand period drives up these aggregators' cost of electricity to such a level that it becomes impossible to compete on profitable terms in the market for aggregation.

Proposition 3 *If an integrated DSO/aggregator is free to allocate all aggregators' demand for electricity, then the only viable market structure is a monopoly where the integrated DSO/aggregator is the sole provider of aggregator services.*

Proposition 3 demonstrates the necessity to regulate integrated DSO/aggregator operations to avoid discrimination. Squeezing competitors out of the market by systematically misallocating their resources in the short-term market is a drastic measure.[17] Such behavior would certainly draw the attention of market monitors and discipline an integrated DSO/aggregator. Still, it is impossible for outsiders to monitor all aspects of network operations because the system operator has private information about network conditions that affect the optimal allocation of demand-shifting and other resources.

[17] In related articles, Weisman (1995) and Economides (1998) analyze the incentive of an integrated upstream monopolist to hurt downstream competitors by selling them inputs of degraded quality. Beard et al. (2001) show that the incentive to commit such sabotage arises in particular under regulation of the upstream firm.

In instances of severe asymmetric information, vertical separation of system operation and aggregator services may be the only way to sustain viable competition. In that case, the DSO merely serves as a platform between aggregators and customers instead of being a participant in the market for aggregation.

4.4 Integrated generator/aggregator

Assume that only one firm participates in the market for aggregation and that this firm also owns a thermal generation facility with production capacity $y > 0$. Let all thermal electricity be competitively supplied.[18] Perfect competition on the production side gives the period i electricity price $p_i = P(q_i) = C'(q_i)$, where $q_i = \tilde{x}_i + s_i - y$ measures residual production. I set $x_i = \tilde{x}_i - y$ to enable comparison with previous results.

The integrated generator/aggregator maximizes

$$\Pi^G(s) = \Pi^{DSO}(s) + [P(x_1 + s) + P(x_2 + \bar{s} - s)]y \tag{11}$$

over s (the production cost of the large generator is uninteresting here because output is fixed at y in each period). The second term represents the revenue from selling y in the short-term market in each period. To ensure strict quasi-concavity of $\Pi^G(s)$, I impose a somewhat stricter boundary condition

$$\frac{C'''(x_i + s_i)}{C''(x_i + s_i)} \max\{x_i; 2\bar{s} + 4y - 4s_i\} < 4 \;\forall s_i \in [0, \bar{s}],\; i = 1, 2 \tag{12}$$

than before on the cost function $C(q)$.[19]

The marginal profit of the integrated generator/aggregator equals

$$\Pi^{GI\prime}(s) = \Pi^{DSO\prime}(s) - [P'(q_2) - P'(q_1)]y.$$

The second part of this expression measures the marginal effect of vertical integration between generation and consumption. The marginal price effect of increasing demand is larger in the peak price than the off-peak price period. The integrated generator/aggregator therefore has an additional incentive to allocate consumption to the peak price period because this reallocation increases the profit on generation (the proof is in Appendix A.3):

Proposition 4 *An integrated generator/aggregator that supplies its thermal generation competitively into the short-term market and has a monopoly in the market for aggregation, consumes less electricity in the off-peak demand period to supply the household energy service than an integrated monopoly DSO/aggregator, but consumption is still larger in the off-peak than the peak demand period* $[\frac{1}{2}\bar{s} < s^G < s^{DSO}]$.

[18] For instance, the integrated generator's production capacity can be so small that it is a profit-maximizing choice to supply the entire capacity into the short-term market in both periods.

[19] The cost function $C(q) = \psi q^{2+\sigma}$, $\psi > 0$, satisfies this stricter boundary condition if $\sigma \max\{1; \frac{2\bar{s}+4y}{x_i}\} \in [0, 4)$.

A well-established result in the analysis of electricity markets is that joint ownership of generation and retail assets may increase efficiency of the short-term market; see for instance Wolak (2007) and Bushnell et al. (2008). Proposition 4 gives the opposite result. Joint ownership of generation and aggregation assets reduces efficiency by exacerbating demand-shifting from the off-peak to the demand peak period compared to a market structure with independent asset ownership, $s^G < s^{DSO} = s^A$, $A = 1$.

Most of the previous literature assumes competitive retail demand for electricity and imperfect competition in production. Integration weakens the incentive of a generation owner with market power to increase electricity prices because doing so reduces the profit of the retail division. I assume competitive supply of generation capacity, but imperfect competition on the demand side. However, that distinction does not make a difference. For instance, integration weakens the incentives of an aggregator with market power to reduce demand in the off-peak demand period because the lower off-peak price reduces the profit of the generation capacity in the off-peak period.

The fundamental difference lies in intertemporal substitution. The integrated aggregator faces an additional benefit of shifting demand from the off-peak to the peak demand period because the higher peak price increases the profit the generation capacity in the peak period. The second effect dominates by the assumption that prices are strictly convex so that the peak price increase is larger in magnitude than the off-peak price reduction, $P'(q_2) > P'(q_1)$.

5 Policy discussion

This section derives policy implications from the equilibrium analysis in the previous section. I first show that one can welfare-rank the different market structures. Second, I derive an efficient regulation of a monopoly aggregator.

5.1 Comparison of market structures

The efficiency with which demand-shifting resources are allocated depends fundamentally on market structure:

Proposition 5 *The market structures for aggregation of demand-shifting resources can be ranked in decreasing order of efficiency:*
(i) $A \geq 2$ *independent aggregators.*
(ii) Integrated DSO/aggregator.
(iii) Integrated generator/aggregator.
(iv) No demand-shifting (passive consumers).

Proof: By way of propositions 1, 2, and 4, it follows that $\frac{1}{2}\bar{s} < s^G < s^{DSO} < s^A < s^{fb}$. This ranking of the equilibrium consumption under the different market structures, and the strict concavity of the welfare function $W(s)$ deliver the result.■

All market structures above are feasible. EU regulation permits vertical integration under certain conditions (Article 35 of EU, 2019). Independent aggregators that do not own any generation capacity also exist. No regulation currently prevents generation owners or retailers from offering aggregation services.

The most efficient market structure is the one in which multiple independent aggregators compete in the market. Competition in the market for aggregation reduces market power in the short-term market. The equilibrium converges to the efficient allocation in the limit when the number of aggregators becomes large. Reducing entry barriers for aggregators therefore is an efficient policy here just as in many other settings.

A central policy question is whether the DSO itself should be involved in the market for aggregation. The welfare effects of vertical integration generally are ambiguous. On the one hand, integration can increase efficiency by eliminating double marginalization. On the other hand, it may lead to foreclosure of downstream competitors. The fact that the DSO is a regulated entity affects this trade-off (Sappington and Weisman, 2021).

In a regulation with full pass-through of costs, an independent DSO has no stake in the short-term market. For instance, it gains nothing from charging market participants transaction fees. Consequently, double marginalization is not an issue. The market structure with an independent DSO and one independent aggregator ($A = 1$) therefore generates exactly the same efficiency as the market structure with a monopoly DSO/aggregator; see Proposition 2.

Instead, foreclosure is a serious welfare concern if the DSO has discrimination over how total aggregation resources are allocated. Systematic misallocation forces competing aggregators out of the market; see Proposition 3. Viable competition under an integrated DSO/aggregator structure commands tight regulatory oversight. Monitoring requires information about all relevant aspects of operating conditions. This problem is aggravated by the multitude of network-specific properties that determine efficient dispatch of resources. The cost of DSO presence in the market for aggregation is likely to exceed the benefits if monitoring is seriously impeded by asymmetric information, and entry barriers for independent aggregators are otherwise low.

A firm active on both sides of the market by producing electricity as well as consuming it through an aggregator, can manipulate prices through demand-shifting even if it does not exploit generator market power. Vertical integration between the production and aggregation is less efficient than independent ownership in this case. However, this inefficiency is never pervasive enough to render aggregation inefficient. Nevertheless, the result suggests that authorities should view integration of generation and aggregation with scrutiny.

5.2 Efficient regulation

Imperfect competition in the market for aggregation generally leads to inefficiencies in the short-term market. An option then could be some type of regulation. To see what efficient regulation might look like in this context, consider an independent aggregator that holds a monopoly position in the market for demand-shifting resources. Assume that this aggregator sells the energy service to households at regulated tariff

$$t = \tfrac{1}{2}(P(x_1 + s) + P(x_1 + \bar{s} - s))\bar{s} - [U(\tfrac{1}{2}\bar{s}) - U(s)] - R(s, \theta).$$

The regulated profit of the aggregator equals $\Pi^R(s) = \Pi(s) - R(s, \theta)$.

The net compensation function

$$R(s, \theta) = \textstyle\int_s^\theta [P'(x_1 + k) + P'(x_2 + \bar{s} - k)](k - \tfrac{1}{2}\bar{s})dk \qquad (13)$$

depends on first-period electricity consumption s and a parameter θ that determines the regulated payment to the household.

The marginal incentive to increase period 1 electricity consumption equals $\Pi^{R\prime}(s) = W'(s)$ for any θ. The marginal payment $\partial R(s, \theta)/\partial s$ neutralizes the aggregator's market power, which perfectly aligns the incentives of the aggregator with those of a central planner.

For the regulated solution to be implementable, it must be both in the aggregator's interest to enter the market for aggregation of demand-shifting resources and for consumers to accept the contract offered by the aggregator. The aggregator's equilibrium profit is $\Pi(s^{fb}) - R(s^{fb}, \theta)$. The household's net benefit of selecting the aggregation contract over the average price contract is $R(s^{fb}, \theta)$. It is strictly better to offer aggregation and consume the efficient amount of electricity s^{fb} than not to enter the market at all, $\Pi(s^{fb}) > 0$.[20] Hence, the participation constraints of the aggregator and of the households are strictly satisfied for θ somewhat above s^{fb} by $R(s^{fb}, \theta) > R(s^{fb}, s^{fb}) = 0$. I summarize these results as follows

Proposition 6 *The compensation function $R(s, \theta)$ characterized in (13) incites an independent aggregator with a monopoly in the market for demand-shifting resources to consume electricity efficiently. There exists a domain of θ such that the aggregator and households participation constraints are satisfied.*

Figure 2 in Section 4.1 illustrates how the compensation payment $R(s^{DSO}, s^{fb})$ aligns marginal incentives with that of the central planned by eliminating the market power gain in period 1 (the dotted area in the figure) and the market power gain in period 2 (the grey area).

6 Conclusion

This paper has explored a two-period model of a short-term electricity market in which smart grid solutions enable third parties to engage in intertemporal substitution of household electricity

[20] An aggregator that consumes $s^{fb}(\mathbf{x})$, $\mathbf{x} = (x_1, x_2)$, in the first period has profit

$$\Pi^{DSO}(\mathbf{x}, s^{fb}(\mathbf{x})) = U(s^{fb}(\mathbf{x})) - U(\tfrac{1}{2}\bar{s}) + [P(x_2 + \bar{s} - s^{fb}(\mathbf{x})) - P(x_1 + s^{fb}(\mathbf{x}))](s^{fb}(\mathbf{x}) - \tfrac{1}{2}\bar{s}).$$

Differentiating with respect to x_2 yields

$$\frac{d}{dx_2}\Pi^{DSO}(\mathbf{x}, s^{fb}(\mathbf{x})) = -\frac{U''(s^{fb})P'(q_2^{fb})(s^{fb} - \frac{1}{2}\bar{s})}{P'(q_1^{fb}) + P'(q_2^{fb}) - U''(s^{fb})} > 0$$

after simplification. Hence, $\Pi^{DSO}(\mathbf{x}, s^{fb}(\mathbf{x})) > \Pi^{DSO}(x_1, x_1, s^{fb}(x_1, x_1)) = 0$ for all $x_2 > x_1$ by $s^{fb}(x_1, x_1) = \frac{1}{2}\bar{s}$.

consumption for the purpose of stabilizing the electricity system. Examples of such demand-shifting resources include indoor temperature control (heating or cooling) or battery charge and discharge. The main purpose was to examine how the structure of the evolving market for aggregation of demand-shifting resources by firms known as aggregators affects the efficiency with which these resources are deployed. Despite its simplicity, the model generates results and policy implications that are likely to be robust and carry over to more general settings.

Aggregators that exercise market power allocate too little demand to the off-peak period. This distortion is smaller if more aggregators are present in the market. I show how an integrated aggregator that also supplies generation to the short-term market in a competitive manner deploys resources *less* efficiently than an independent aggregator. I characterize a regulatory policy that can implement the efficient allocation on the basis of data that can be obtained from the short-term market.

Short-term markets are usually run by the distribution system operator (DSO) that owns the local network. The interaction between system operation and the market for demand-shifting resource represents a key policy concern. I show that the DSO has an incentive to dispatch electricity inefficiently if it holds a controlling stake in an aggregator. Moreover, an integrated DSO/aggregator can under certain circumstances foreclose competitors in the market for aggregation if left unsupervised. This foreclosure takes the form of misallocating competing aggregators' demand-shifting resources.

Competition concerns suggest that system operation may best be separated from the market for aggregation. Viable competition in the market for aggregation may be infeasible for other reasons, leaving aggregation to the DSO itself or a subsidiary as the only option. Still, a monopoly integrated DSO/aggregator delivers a more efficient market outcome than a benchmark where the demand-shifting potential remains untapped.

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Appendix

A.1 Proof of Proposition 2

Characterization. The function

$$H(A,s) = U'(s) - P(x_1+s) + P(x_2+\bar{s}-s) - \frac{1}{A}[P'(x_1+s) + P'(x_2+\bar{s}-s))](s-\tfrac{1}{2}\bar{s})$$

characterizes the profit of increasing first period energy consumption marginally above s evaluated at $s_a = s$ for all $a = \{1,...,A\}$. Seeing as $H(A,s) > 0$ for all $s \leq \frac{1}{2}\bar{s}$ and $H(A,s) < 0$ for all $s \geq s^{fb}$, all symmetric equilibria are interior, $s^A \in (\frac{1}{2}\bar{s}, s^{fb})$, and solve the first-order condition $H(A,s^A) = 0$. By the properties of $U(s)$, $C(q_i)$ and bounded elasticity (6),

$$\frac{\partial H(A,s)}{\partial s} = U''(s) - \sum_{i=1,2} \frac{C''(x_i+s_i)}{A^2}[2A - \frac{C'''(x_i+s_i)}{C''(x_i+s_i)}(\frac{\bar{s}}{2} - s_i)] < 0$$

for all $s \in [\frac{1}{2}\bar{s}, s^{fb}]$. Hence, there is a unique symmetric equilibrium candidate $s^A \in (\frac{1}{2}\bar{s}, s^{fb})$. Strict monotonicity of $H(A,s)$ in s,

$$H(A,s^{DSO}) = \frac{A-1}{A}W'(s^{DSO}) + \frac{1}{A}\Pi^{DSO\prime}(s^{DSO}) = \frac{A-1}{A}W'(s^{DSO}),$$

and $W'(s^{DSO}) > 0$ imply $s^A \geq s^{DSO}$ with strict inequality if $A \geq 2$.

The linear function

$$\rho\frac{1}{A}\frac{A-1}{A}(\Pi^A(s^A) - b) - \frac{1}{A}$$

measures the profit of increasing the benefit of joining aggregator a marginally above b if $b_{a'} = b$ for all $a' = \{1,...,A\}$. It is then straightforward to solve for the symmetric equilibrium candidate (9).

Comparative statics Increasing the number of aggregators in the market, increases efficiency: $\frac{\partial s^A}{\partial A} = -\frac{\partial H/\partial A}{\partial H//\partial s} > 0$ by $\partial H/\partial A = \frac{1}{A^2}[P'(q_1^A) + P'(q_2^A)](s^A - \frac{1}{2}\bar{s}) > 0$. Aggregator profit $\Pi^A(s^A)$ is strictly decreasing in A: $\frac{d}{dA}\Pi^A(s^A) = -(A-1)W'(s^A)\frac{\partial s^A}{\partial A} < 0$.

Existence. Assume that $(b_{a'}, s_{a'}) = (b^A, s^A)$ for all $a' \neq a$, and consider the profitability of a deviation by a to $b_a \geq 0$ and $s_a \in [0,\bar{s}]$ with associated market share L_a. Observe that $s = L_a s_a + (1-L_a)s^A$. Seeing as

$$\frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a} - \frac{\bar{s}}{2} = \frac{L_a(x_2-x_1) + 2(1-L_a)(\frac{x_2-x_1+\bar{s}}{2} - s^A)}{2L_a} > 0$$

$\frac{\partial \Pi^a}{\partial s_a} > 0$ for all $s_a \leq \frac{1}{2}\bar{s}$ and $\frac{\partial \Pi^a}{\partial s_a} < 0$ for all $s_a \geq \frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a}$. Hence, the profit-maximizing choice s_a is contained in $(\frac{1}{2}\bar{s}, \frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a})$ for any b_a

The first term in the partial second-derivative

$$\frac{\partial^2 \Pi^A}{\partial s_a^2} = U''(s_a) - L_a P'(x_1+s)[2 + \frac{C'''(x_1+s_1)}{C''(x_1+s_1)} L_a(s_a - \tfrac{1}{2}\bar{s})] - L_a P'(x_2+\bar{s}-s)[2 - \frac{C'''(x_2+s_2)}{C''(x_2+s_2)} L_a(s_a - \tfrac{1}{2}\bar{s})],$$

is non-postitive, whereas the second is strictly negative for all $s_a \geq \frac{1}{2}\bar{s}$. Possible ambiguity concerns the third term in brackets, which one can write as

$$\begin{aligned} 2 - \frac{C'''(x_2+s_2)}{C''(x_2+s_2)} L_a(s_a - \tfrac{1}{2}\bar{s}) &= 2 - \frac{C'''(x_2+s_2)}{C''(x_2+s_2)} \frac{x_2 - x_1}{2} \\ &\quad + \frac{C'''(x_2+s_2)}{C''(x_2+s_2)}[(1-L_a)(s^A - \tfrac{1}{2}\bar{s}) + L_a(\frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a} - s_a)] \end{aligned}$$

after rearrangement. The expression on the right-hand side of the first row is strictly positive by assumption (6). The expression on the second row is non-negative for all $s^A \geq \frac{1}{2}\bar{s}$ and $s_a \leq \frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a}$. Hence, $\partial^2 \Pi^a / \partial s_a^2 < 0$ for all $s_a \in [\frac{1}{2}\bar{s}, \frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a}]$. The solution $\partial^2 \Pi^a(b_a, S)/\partial s_a = 0$ therefore uniquely defines the profit-maximizing $S(b_a) \in (\frac{1}{2}\bar{s}, \frac{x_2 - x_1 + \bar{s} - 2(1-L_a)s^A}{2L_a})$. Consider next the profit-maximizing choice of b_a. Let $\pi^A(b_a) = L_a[\Pi^A(S(b_a)) - b_a]$. Define $\bar{b}$ as the largest solution to $\Pi^A(S(b)) - b = 0$. The profit-maximizing choice of b is contained in $[0, \bar{b}]$. By the envelope theorem,

$$\pi^{A\prime}(b_a) = \frac{\partial L_a}{\partial b_a}(\Pi^A(S(b_a)) - b_a) - L_a[1 - \frac{\partial \Pi^A}{\partial L_a}\frac{\partial L_a}{\partial b_a}]$$

where

$$\frac{\partial \Pi^A}{\partial L_a} = -[P'(x_1 + L_a s_a + (1-L_a)s^A) + P'(x_2 + \bar{s} - L_a s_a - (1-L_a)s^A)](s_a - s^A)(s_a - \tfrac{1}{2}\bar{s})$$

The second-derivative of this profit function equals

$$\begin{aligned} \frac{\pi^{A\prime\prime}(b_a)}{\partial L_a/\partial b_a} &= \rho L_a[(1-2L_a)(\Pi^A - b_a + L_a \frac{\partial \Pi^a}{\partial L_a}) \\ &\quad + (1-L_a)(2\frac{\partial \Pi^a}{\partial L_a} + L_a \frac{\partial^2 \Pi^a}{\partial L_a^2} + \frac{\partial^2 \Pi^a}{\partial L_a \partial s_a} L_a \frac{\partial s_a}{\partial L_a})] - 2 \end{aligned}$$

where I have used $\frac{\partial L_a}{\partial b_a} = \rho L_a(1-L_a)$, $\frac{\partial^2 L_a}{\partial b_a^2} = \rho L_a(1-2L_a)\frac{\partial L_a}{\partial b_a}$. The expression inside the square brackets is bounded and therefore strictly below 2 for ρ sufficiently small. Hence, $\pi^{A\prime\prime}(b_a) < 0$ for all $b_a \in [0, \bar{b}]$ if ρ is sufficiently small, in which case $b_a = b^A$ constitutes a best-response to the other aggregators' choice of b^A. Under symmetric market shares, $s_a = s^A$ represents a best-response to the other aggregators' choice of s^A.■

A.2 Proof of Lemma 1

Part (i) of the proposition. The integrated DSO/aggregator maximizes $\Pi^M(z, y)$ defined in

(10) over $(z, y) \in [0, \bar{s}]^2$. The marginal profit of increasing electricity consumption z of the own aggregator entity equals

$$\frac{\partial \Pi^M(z,y)}{\partial z} = U'(z) - P(x_1+s) + P(x_2+\bar{s}-s) - L[P'(x_1+s) + P'(x_2+\bar{s}-s)](z - \tfrac{1}{2}\bar{s}),$$

whereas the marginal profit of increasing electricity consumption y of the other aggregators equals

$$\frac{\partial \Pi^M(z,y)}{\partial y} = -(1-L)[P'(x_1+s) + P'(x_2+\bar{s}-s)](z - \tfrac{1}{2}\bar{s}).$$

There are three possible solutions to the DSOs maximization problem.

The first possibility is $z > \frac{1}{2}\bar{s}$. In this case, $y = 0$ by $\partial \Pi(z,y)/\partial y < 0$. Observe that $\partial \Pi(z,0)/\partial z > 0$ for all $z \leq \frac{\bar{s}}{2} < \frac{x_2 - x_1 + \bar{s}}{2L}$ because then $P(q_2) > P(q_1)$, and $\partial \Pi(z,0)/\partial z < 0$ for all $z \geq \frac{x_2 - x_1 + \bar{s}}{2L} > \frac{\bar{s}}{2}$ because then $P(q_2) \leq P(q_1)$. Hence, there exists a profit-maximizing $z^M \in (\frac{\bar{s}}{2}, \frac{x_2 - x_1 + \bar{s}}{2L})$ if $y^M = 0$. The profit at this local optimum satisfies $\Pi(z^{DSO}, 0) > 0$ by $\partial \Pi(\bar{s}/2, 0)/\partial z > 0$, and $\Pi(\bar{s}/2, y) = 0$.

The second possibility is $z = \frac{1}{2}\bar{s}$. However, $(\frac{1}{2}\bar{s}, y)$ is dominated by $(z^M, 0)$ since $\Pi^M(z^M, 0) > 0 = \Pi^M(\frac{1}{2}\bar{s}, y)$ for all $y \in [0, \frac{1}{2}\bar{s}]$.

The third possibility is $z < \frac{1}{2}\bar{s}$. In this case, $y = \bar{s}$ is optimal by $\partial \Pi^M(z,y)/\partial y > 0$. Observe that $\partial \Pi(z,\bar{s})/\partial z > 0$ for all $z < \min\{\frac{\bar{s}}{2}; \frac{x_2 - x_1 + \bar{s} - 2(1-L)\bar{s}}{2L}\}$ because then $P(q_2) > P(q_1)$, and $\partial \Pi(z,\bar{s})/\partial z < 0$ for all $z > \max\{\frac{\bar{s}}{2}; \frac{x_2 - x_1 + \bar{s} - 2(1-L)\bar{s}}{2L}\}$ because then $P(q_2) < P(q_1)$. There exists a profit-maximizing solution $z \in (\frac{x_2 - x_1 + \bar{s} - 2(1-L)\bar{s}}{2L}, \frac{\bar{s}}{2})$ to $y = \bar{s}$ if and only if $x_2 - x_1 < \bar{s}$ and $L < 1 - \frac{x_2 - x_1}{\bar{s}}$ because these are a necessary and sufficient conditions for $\frac{x_2 - x_1 + \bar{s} - 2(1-L)\bar{s}}{2L} < \frac{\bar{s}}{2}$. I now verify that $(z^M, 0)$ is strictly more profitable than any local optimum $z < \frac{1}{2}\bar{s}$, $y = \bar{s}$. To do so, compare the profit

$$\Pi^M(\tfrac{1}{2}\bar{s} - \alpha, \bar{s}) = U(\tfrac{1}{2}\bar{s} - \alpha) - U(\tfrac{1}{2}\bar{s}) + [P(x_1 + \bar{s} - L(\tfrac{1}{2}\bar{s} + \alpha)) - P(x_2 + L(\tfrac{1}{2}\bar{s} + \alpha))]\alpha$$

of arbitrary electricity demand $z = \frac{1}{2}\bar{s} - \alpha$, $\alpha \in (0, \frac{1}{2}\bar{s}]$, $y = \bar{s}$, with profit

$$\Pi^M(\tfrac{1}{2}\bar{s} + \alpha, 0) = U(\tfrac{1}{2}\bar{s} + \alpha) - U(\tfrac{1}{2}\bar{s}) + [P(x_2 + \bar{s} - L(\tfrac{1}{2}\bar{s} + \alpha)) - P(x_1 + L(\tfrac{1}{2}\bar{s} + \alpha))]\alpha$$

for electricity demand $\tilde{z} = \frac{1}{2}\bar{s} + \alpha$, $\tilde{y} = 0$. The difference can be written as

$$\begin{aligned} \Pi^M(\tfrac{1}{2}\bar{s} + \alpha, 0) - \Pi^M(\tfrac{1}{2}\bar{s} - \alpha, \bar{s}) = & \; U(\tfrac{1}{2}\bar{s} + \alpha) - U(\tfrac{1}{2}\bar{s} - \alpha) \\ & + \; \alpha \int_{x_1}^{x_2} [P'(x + L(\tfrac{1}{2}\bar{s} + \alpha)) + P'(x + \bar{s} - L(\tfrac{1}{2}\bar{s} + \alpha))] dx > 0. \end{aligned} \tag{14}$$

The utility difference on the first row is non-negative. To see this, observe that $U(\frac{1}{2}\bar{s} + \alpha) - U(\frac{1}{2}\bar{s} - \alpha)$ is a convex function by

$$\frac{d}{d\alpha}[U'(\tfrac{1}{2}\bar{s} + \alpha) + U'(\tfrac{1}{2}\bar{s} - \alpha)] = U''(\tfrac{1}{2}\bar{s} + \alpha) - U''(\tfrac{1}{2}\bar{s} - \alpha) \geq 0,$$

as $U'''(s) \geq 0$ by assumption. The function $U(\frac{1}{2}\bar{s} + \alpha) - U(\frac{1}{2}\bar{s} - \alpha)$ reaches a global minimum at $\alpha = 0$ because $U'(\frac{1}{2}\bar{s}) + U'(\frac{1}{2}\bar{s}) = 0$. Therefore, $U(\frac{1}{2}\bar{s}+\alpha) - U(\frac{1}{2}\bar{s}-\alpha) \geq U(\frac{1}{2}\bar{s}) - U(\frac{1}{2}\bar{s}) = 0$ for all $\alpha \in (0, \frac{1}{2}\bar{s}]$. The expression on the second row of (14) is strictly positive for $\alpha > 0$ by $x_2 > x_1$. Collecting inequalities yields $\Pi^M(z^M, 0) \geq \Pi^M(\frac{1}{2}\bar{s}+\alpha, 0) > \Pi^M(\frac{1}{2}\bar{s}-\alpha, \bar{s}) = \Pi^M(z, \bar{s})$ for all $z < \frac{1}{2}\bar{s}$. Hence, every local optimum with the property $z < \frac{\bar{s}}{2}$ is strictly dominated by $z^M > \frac{\bar{s}}{2}$ and $y^M = 0$. Part (ii) of the proposition is trivial because $z^M < \bar{s}$ implies $s^M = Lz^M + (1-L)y^M = Lz^M < \frac{1}{2}\bar{s}$ if $L < \frac{1}{2}$.■

A.3 Proof of Proposition 4

The second derivative of $\Pi^G(s)$ can be written as

$$\Pi^{G''}(s) = U''(s) - \sum_{i=1,2} C''(x_i + s_i)[2 - \frac{C'''(x_i + s_i)}{C''(x_i + s_i)}(\tfrac{1}{2}\bar{s} + y - s_i)] < 0,$$

which establishes strict concavity of $\Pi^G(s)$ by assumption (12). $s^G < s^{DSO}$ then follows from $\Pi^G(s^{DSO}) < 0$. Moreover, $\Pi^{G\prime}(\frac{1}{2}\bar{s})|_{x_2=x_1} = 0$ and

$$\frac{\partial}{\partial x_2}\Pi^{I\prime}(\frac{\bar{s}}{2}) = C''(x_2 + \frac{1}{2}\bar{s})[1 - \frac{C'''(x_2 + \frac{1}{2}\bar{s})}{C''(x_2 + \frac{1}{2}\bar{s})}y] > 0.$$

imply $s^G > \frac{1}{2}\bar{s}$ for all $x_2 > x_1$ by strict concavity of $\Pi^G(s)$.■