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Sharing is not Caring: Backward Integration of Consumers

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Sharing is not Caring: Backward Integration of Consumers

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Abstract

A new type of player occurs in the sharing economy: a vertically integrated consumer who owns production facilities and has direct market access, often termed "active prosumer". The prosumer faces a trade-off between market transaction cost and substantial strategic potential to influence both market demand and supply by her decisions. We discuss optimal marketing and production decisions in light of this trade-off. An empirical application to the German-Austrian electricity market demonstrates substantial incentives for active market participation by recently added decentralized renewables production. Prosumers can achieve considerable profit increases by switching roles of net market supplier or customer.

Keywords: Active Prosumer, Capacity Withholding, Self-Supply, Vertical Integration, Consumer Production, Market Participation Cost

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I Introduction

Technological developments allow for new levels of information aggregation and thereby before unthought-of market participation. On the one hand, using decentralized information (or knowledge) is known to be one of the major drivers of efficiency as discussed already in Hayek (1945). Lowering entry cost will typically lead to new market participants of comparably small scale as is the case for the sharing economy. Offering own living space or the own car is a massive business case due to low-transaction cost platforms such as AirBnB or Uber. Textbook economics will then tell a story of polypolistic competition leading to efficiency gains. On the other hand, however, an interesting and largely ignored aspect of this phenomenon is that these "prosumers" are typically vertically integrated, combining both production and consumption (Toffler 1980). Usually vertical integration refers to firms selling to consumers, whereas prosumers are of particular interest because the demand side is directly involved in the integration process and strategically participates on the market.

Hence, we address the following questions: How will a marginal, vertically integrated market participant facing residual supply and residual demand consume and produce? What are the incentives of these new participants when they are small and – exceeding the case of the pure sharing economy – when they become bigger? How do these incentives change when market conditions vary?

In this paper, first, a theoretical model sheds light on supply and demand incentives for differently sized prosumers. This new type of player in the market changes her strategic role and decides about her degree of market participation in contrast to self-supply. The prosumer can withhold supply as well as demand thereby increasing her lever for strategic behavior or, in other words, for the exercise of market power. Her optimal decision is shown to depend on current market conditions such as the price elasticity of the prosumer market supply and demand as well as own and market marginal cost. Second, an empirical application to the electricity sector in Germany serves to investigate the incentives of the vertically bundled prosumer. We deem this sector to be particularly interesting, because two recent developments led to a new type of "gentailer": First, the decentralization of power generation increases, fueled by decreasing investment costs for e.g. photovoltaic systems or wind turbines rendering small scale generation viable (IEA Wind 2015, IRENA 2016, Comello & Reichelstein 2016). Second, the ownership structure changes from a traditional system of few big generation firms towards fragmented generation being owned and operated by small agents, such as homeowners or farmers. These own about 80% of German photovoltaics capacity being connected to the low voltage network (see Hanna et al. 2017, Kairies et al. 2016).[1] Initially, generous feed-in-tariffs led to passive supply to the market. Gradually declining they fell below the average retail electricity price in Germany for the first time in January 2012 (BMJ 2017). This might mark the change to the active prosumer. This path may be guided in the future by increasing automation of the smart home, but already started by "aggregators", companies aggregating demand or supply, such as Statkraft. We demonstrate how these differently sized market participants are able to strategically influence the market price and increase own profits. Moreover, this application is particularly interesting because of the many dynamic switches of the strategic role of the prosumer, oscillating between residual monopsonist and residual monopolist (i.e. demand-only and supply-only situations).

Today it is still the most common way for a prosumer to participate in the electricity market passively serving own demand first and selling solely excess capacity to a load-serving entity (LSE) or distribution system operator (DSO) at a predetermined, fixed price.[2] Thereby the prosumer is deprived of any adaption to dynamically changing market conditions. Hence, we term this agent "passive prosumer". In contrast, the "active prosumer" currently gains importance as a recent report by EPEXSpot, a European electricity traders' association, underlines (Töpfer et al. 2017). In contrast to small consumers such as households still waiting for the technological preconditions enabling them to play an active role in the market, so-called "aggregators" already participate in the game today. These companies directly offer production on the markets aggregating multiple production units and, furthermore, they behave strategically adapting their bidding behavior to (negative) market prices as an analysis of aggregated day-ahead bidding functions shows. The European Commission acknowledges their importance by including the following definition into their 'Winter Package on common rules for the European electricity market': aggregators are "market participant[s] that combine [. . .] multiple customer loads or generated electricity for sale, for purchase or auction in any organised energy market." (EC 2007)[3,4] This development is similar to other markets, where service providers take over the role of aggregators. These parallels can be found with Uber aggregating supply to find differentiated, time-dependent prices for a request, or tour operators starting to offer mini-bus rides. Similarly, services handle keys through AirBnB and allow for price information exchange influencing pricing of flats. However, in other markets prosumers are already comparably big: Amazon and Google e.g. can use their servers for own calculations and services or sell the computing power on according spot markets.

The application to the German-Austrian electricity market demonstrates the empirical relevance of these theoretical considerations. Estimating market demand and supply functions from bid data we simulate how varying production capacity impacts the prosumer's incentive to optimally bid into the market and produce for own consumption. This market power effect is shown to increase whenever capacity increases similar to many models analyzing abusive market power. This case is particularly interesting, because even for very small prosumers or aggregators and in less tight equilibria, it is shown to be optimal for the prosumer to influence the market equilibrium. We investigate varying scarcity situations throughout the 8760 hours of the year[5]. This differs from typical models of market power where market power issues mainly arise in peak hours whereas there are no or little markups in off-peak hours (see e.g. Joskow & Tirole (2007), Borenstein et al. (2002), Wolak (2003)). The prosumer may raise her profit per production unit from 0.5 to 10.2 EUR/MWh even in the range of moderate market shares from marginal size up to 10 % of maximum demand.

In the general setup of our model, however, we abstract from the electricity market and focus on the strategy to decide for each period about the quantity offered and demanded on the market. The insights are then also useful for other markets where the decision between self-supply and offering a good on the market matters. Depending on the prosumers' marginal cost and the relation of the prosumer's production capacity (or actual production) to his demand, we find it to be optimal for the prosumer to strategically offer or withhold demand and supply capacity around the market equilibrium. Thereby she can shift the industry's aggregate demand and supply functions in two directions: the prosumer can try to increase the market clearing price e.g. by adding her demand to the market and thus benefit from this higher price with all of his production or by withholding part of his production capacity; or she can try to decrease the market clearing price e.g. by offering as much generation capacity as possible. Important requirements are the possibility to actually participate and bid in a market, e.g. via a trading license; and an independent market maker who aggregates demand and supply bids to determine a unique market clearing price. In the electricity market, these requirements are fulfilled e.g. at the day-ahead market at EPEXSpot.

We investigate optimal sales and sourcing as well as production decisions of a vertically integrated customer who owns production facilities[6]. She faces both an elastic market demand and supply. Moreover she faces a fixed per-unit cost of trading on the market, in particular transaction cost (e.g. trading cost, act of renting out apartment), transport cost (e.g. electricity network usage) and own opportunity cost (e.g. reduction of consumption (renouncing on living space)). Thereby, the prosumer has a strategic potential to influence the market price, but it depends on her entry cost[7]. This is in the spirit of a Cournot game, in which the player can also change the market price altering total market quantity. In contrast, in this paper market opponents do not react. The focus is on the prosumer's incentives to influence the market price, whereas the reactions of other players are, first, second order effects and, second, straightforward and known from the literature. Third, this exogenous treatment of the market equilibrium has the very pragmatic advantage that it offers the possibility to ignore market power issues in the rest of the market. In peak load systems, such as electricity, market power varies on an hourly basis. Modeling prosumer behavior as a decision problem thus is an elegant and realistic way of investigating her optimal production and trading decisions. It is discussed theoretically how the prosumer makes optimal sales and sourcing as well as production decisions and thereby influences supply and demand to increase her profits.

Two facts are worth mentioning with regard to characteristics of trading markets. First, it is completely rational to be supplier and customer at the same time. This is a well-known result in the finance literature derived from the market participants' need to hedge market risks. In the PJM electricity market, Longstaff & Wang (2004) find all wholesale market participants to take an active role as supplier, customer or both at any point in time (see p. 5). They also find empirical evidence for results shown by (Bessembinder & Lemmon 2002) indicating that producers and retailers have an incentive to hedge forward, in turn appearing as both short term market customers and suppliers. Intermediate wholesale market risk can be either hedged or avoided by vertical integration, which makes the latter rational whenever the first is not perfectly consumable. However, production cost as well as retail demand risk prevail making simultaneous supply and demand side bids rational. It is therefore not surprising to find our prosumer to switch between the different roles as a (residual) monopolist and monopsonist and many hybrid cases in between[8]. Second, vertical integration may be advantageous[9]. Raising rival's cost is a classical example (see e.g. Ordover et al. (1990), Salinger (1988), Riordan (1998), Hastings & Gilbert (2005), Riordan (2008), Spiegel (2013)). Without further structural adjustments of competitors (vertical integration on their part), the integrated firm can increase sales and profits or even drive the worse firm out of the market. In addition to arguments already discussed in this stream of literature, we consider costs of market participation, which represents only an option for a consumer, and the option of altering market demand. In particular for smaller prosumers we find it unprofitable to influence the market equilibrium. However, this changes considerably already for small market shares, which can easily be achieved by aggregators such as Vattenfall on the German market (see Töpfer et al. 2017).

The closest analytical description of prosumers in particular can be found in literature on vertical integration, in particular with Bushnell et al. (2008) and Mansur (2007). Both contributions are based on so-called "gentailers", i.e. electricity generating companies integrated to the retail market, who still have to forecast their final customers' demand. The authors incorporate the internal procurement of electricity as long(er) term bilateral contracts, with the gentailer ultimately showing up either as net-seller or net-buyer on the (day-ahead) market. However, since they argue that retail prices are usually highly regulated and hence predetermined, as well as that demand is perfectly inelastic, any strategic component of self-supply vs. market participation is missing. This also holds for Boom (2009) who introduces retail competition by enabling consumers to switch to the retailer with the lower price. In contrast to e.g. avoiding double marginalization, we argue that organizational theories explaining vertical integration e.g. via transaction costs or enhanced decision rights do not apply for small scale prosumers. This is because contracts with a local load-serving entity which also includes supply security compares to the risk of investing in own generation along with the financial burden and the complex possibilities of selling the production in the different electricity markets (see Bresnahan & Levin 2012, Joskow 2010).

Prosumers as new market participants also receive particular attention in electricity market literature. This includes a special issue in the IAEE Journal "Economics of Energy & Environmental Policy" (2017, Vol 6/1) on ProSumAge, i.e. prosumers who also have the possibility to store their generation (see Green & Staffell 2017). In general, the contributions focus either on the use of flexibility or storage for optimal bidding strategies e.g. during the day (e.g. Shirazi & Jadid 2017, Ottesen et al. 2016); or on system models extended by allowing for prosumers to participate: the result of the prosumer's profit maximization serves as input for a cost minimization problem of an independent system operator who is supposed to find the least expensive way to meet demand when also taking transmission line constraints, loop flows etc. into account (e.g. Rigo-Mariani et al. 2014, Schill et al. 2017). These applied simulations, however, usually consider the market clearing price as exogenous to the prosumers' decisions.

To summarize, we claim that there is a new kind of agent, the active prosumer, who has a new possibility to participate in the market. To address the issue of implications for the market and whether active participation actually is profitable, we set up a theoretical model in section

II to analytically derive the optimal decisions for a single prosumer facing a competitive fringe, relaxing the price taking assumption. We show conditions for when and how to adjust market participation to yield a profit gain compared to passive presumption, which depends on the marginal costs of the prosumers' production unit, demand and supply elasticities as well as on the relation of prosumer's own demand and production capacity. Section III contains an empirical calibration of the model, based amongst others on hourly demand elasticities estimated using bidding data from the German-Austrian day-ahead electricity market. We illustrate the bandwidth of different prosumer sizes ranging from the small household up to classical production and retail supply companies, who might take over the role as an "aggregator". Depending on the technology used and the according prosumer's production costs we find many strategic role switches and altering bidding behavior. We discuss the results and conclude in section V.

II The Model

Nomenclature

q_d^{PS}	demand purchased on the market	p_s, p_d	inverse supply and demand functions
q_s^{PS}	production offered on market	a_s, a_d	intercepts of supply and demand functions
c^{PS}	production costs of prosumer's production unit	Q_s^{PS}	production capacity of prosumer
c^{market}	maximum costs of generating units available	Q_d^{PS}	capacity needed to satisfy own demand
η_d	slope of demand function	Q_d^{market}	maximum market demand (excl. prosumer)
η_s	slope of supply function	Q_s^{market}	production capacity of competitive fringe

II(i). Model Setup

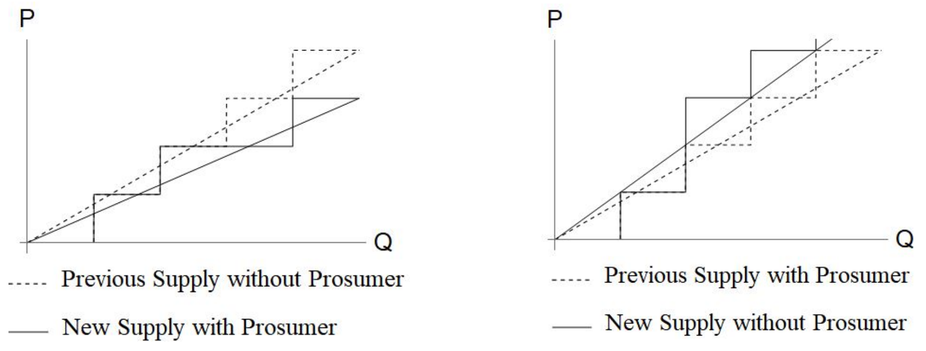
Our modelling framework comprises a residual prosumer optimizing profit in a market with given demand and supply. The prosumer's profit is π^{PS} (see Equation (1)), where $p^* = f(q_s^{PS}, q_d^{PS})$ denotes the market clearing or equilibrium price and τ the additional costs for purchasing on the retail market, like e.g. transaction or transmission costs. The three terms capture, first, the revenues from selling production, second, the costs for covering (remaining) demand on the retail market, and third, the prosumer's costs for using the production unit. Note that the objective function does not contain any utility the prosumer may gain from using the amount demanded in each period. We assume that the demand in one period is fixed and the only consideration that remains for the prosumer is how to cover this demand at minimum costs.

$$\pi^{PS}_{(q^{PS}_s, q^{PS}_d)} = p^*(q^{PS}_s) - (p^* + \tau)(q^{PS}_d) - c^{PS}(q^{PS}_s + Q^{PS}_d - q^{PS}_d) \quad (1)$$

The prosumer has the following two decision variables: First, q^{PS}_s denotes how much production capacity Q^{PS}_s is offered on the market; and second, q^{PS}_d denotes the amount the prosumer purchases on the market. We impose the restriction that the prosumer's demand Q^{PS}_d must be fulfilled at every instant and that shifting or withholding demand is not possible. Hence, own production capacity must be used for residual demand $q^{PS}_{own} = Q^{PS}_d - q^{PS}_d$, i.e. for self-supply. However, q^{PS}_{own} and q^{PS}_s do not have to add up to total production capacity, i.e. the prosumer can withhold capacity from the market e.g. by choosing to use this capacity on a different, e.g. subsequent, market or by withholding it completely. We assume that the prosumer does not incorporate possible profits on other markets into his optimization. Since our model is deterministic and the prosumer has perfect foresight of (his influence on) the market clearing price, assumptions regarding the prosumer's risk attitudes are not necessary.

This unique market clearing price p^* is determined for each hour by an independent authority that collects and aggregates demand and supply bids – i.e. price-quantity combinations – and intersects the resulting step functions. We deviate from the fact that these aggregated supply and demand functions are step functions by approximating them linearly. Most importantly, we allow the prosumer to actively participate on both sides of the market by deciding whether to enter the market and to thereby introduce a step or not. Figure 1 depicts the effect of adding a step to the supply function – the same logic also applies to the demand side of the market. The new, dashed step function is again approximated by a linear function (dashed).

The demand and supply functions, p^d and p^s, respectively, are stated in Equations (2) and (3). It is important to note that in this linear setup the maximum willingness to pay of



(a) (b)

Figure 1: Schematic PS Effects on the Supply Function: (a) PS Enters, and (b) PS Exits the Market

demand a_d, the minimum ask price of supply a_s, and the maximum production costs c^{market} do not change when a prosumer enters or exits the market. This results in a rotation of the functions, i.e. a slope change and constant intercepts.[10] The parameters $\eta_d = \frac{a_d}{Q_d^{market}}$ and $\eta_s = \frac{(c^{market} - a_s)}{Q_s^{market}}$ denote the slopes of the demand and supply function as ratios of vertical and horizontal intercepts/cutoff points; $\alpha = \frac{q_d^{PS}}{Q_d^{market}}$ and $\beta = \frac{q_s^{PS}}{Q_s^{market}}$ incorporate the respective market size of the prosumer and depict the impact of the prosumer's decision variables on the slopes. If the prosumer decides to not participate in the market, $\alpha = \beta = 0$ and the slopes remain unchanged; if he participates, $\frac{dp^d}{d\alpha} > 0$ and $\frac{dp^s}{d\beta} < 0$ holds; and $Q = [q_{PS}, q_{-PS}]$ denotes the amounts produced and demanded at the time of delivery, i.e. the quantities all the market participants committed themselves to.

(2) $$p^d_{(Q,\alpha(q_d^{PS}))} = a_d - \eta_d(1+\alpha)^{-1} \cdot Q$$

(3) $$p^s_{(Q,\beta(q_s^{PS}))} = a_s + \eta_s(1+\beta)^{-1} \cdot Q$$

We also assume that the prosumer demands at every possible price based on the idea that in the short term demand cannot be shifted, i.e. the prosumer's individual demand function is completely inelastic. In addition, the prosumer also cannot shift his supply e.g. by storing production. This does, however, not affect our results, because the prosumer does take production costs c^{PS} into account for deriving the optimal bids (see Section II(iii).) and does not produce, if $p^* < c^{PS}$. Modeling demand and supply as nonlinear functions would potentially allow us to better depict e.g. increasing marginal costs of additional supply based on different production technologies. However, whereas the effects to be shown remain the same this unnecessarily complicates the optimization, and the empirical calibration in Section III allows us to depict different effects of the prosumer's supply and demand decisions on the market clearing price as it is based on different elasticities and hence on different slopes for each hour.

The prosumer's decisions affect both functions simultaneously which leads to a multiplicity of realizable market clearing prices depicted by the shaded area ABCD in Figure 2. Point A with the according market clearing price p_A and quantity q_A results whenever the prosumer decides to not participate in the market at all, i.e. by either producing exactly the amount needed for self-supply or by reducing overall demand to 0 (not possible in our setup). In B the prosumer satisfies all of his demand with his own production and offers excess production on the market. Combination C is attained with full market participation of the prosumer on both the demand and the supply side, and D depicts the situation of a pure consumer, i.e. without making use of any production capacity. Any equilibrium in the lighter shaded area BEC cannot be reached, because whenever the prosumer reduces his market demand q_d^{PS} he has to use part of his own production capacity thereby also limiting or reducing the possible impact on the supply function.

A few crucial assumptions also need to be addressed: First, we depict the market environment as a uniform-price double-sided call auction with Cournot competition. Relaxing the price-taking assumption, the prosumer decides about the quantities to place in the auction, being faced with a price-taking competitive fringe. Furthermore, we assume that the production capacity has already been built which leaves only the decision about how to optimally use it in the market. In addition, the installed production capacity in the market, $Q_s^{market} + Q_s^{PS}$, is always high enough to provide even the highest possible demand (including the prosumer), i.e. shortages cannot occur and importing is not necessary. Lastly, we focus on repeating short term decisions – e.g. on a market where these auctions are held hourly leading to hourly market clearing prices – and we exclude the possibility to store production or to shift demand in time to benefit from or to avoid high prices, respectively. Even though this paper

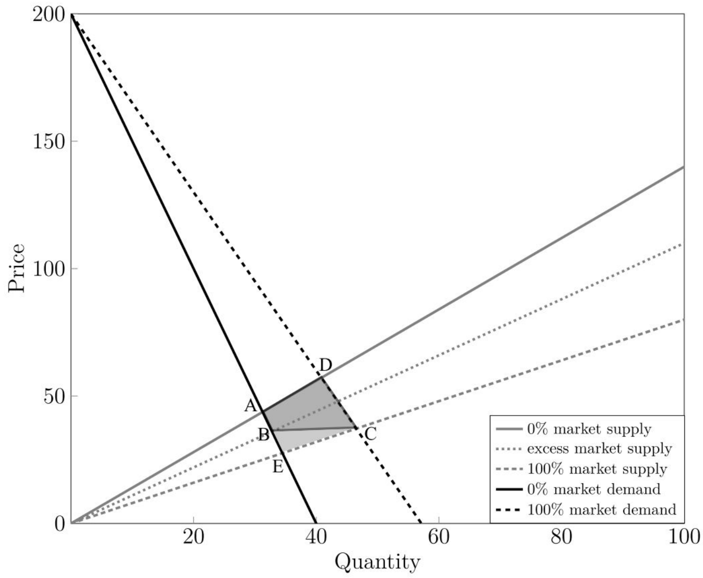


Figure 2: Window of Attainable Market Clearing Prices and Quantities

and the model are motivated by the German-Austrian hourly day-ahead auctions held by EPEXSpot as well as by characteristics of the electricity markets, the general model applies to any situations where the assumptions above are met.

II(ii). Optimal Prosumer Behavior

In their most general form, the effects of the decision variables can be disentangled into direct and indirect effects, captured in Equations (4) and (5) by the first and second terms, respectively. For completeness, we also display the intermediate effects of q_d^{PS} and q_s^{PS} on α and β where we can see that the indirect effects have different signs because $\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} > 0$ and $\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} < 0$. Note that these fractions implicitly contain the demand and supply elasticity, respectively.

$$\frac{d\pi}{dq_d^{PS}} = \frac{\partial \pi}{\partial q_d^{PS}} + \frac{\partial \pi}{\partial p^*}\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} \tag{4}$$

$$\frac{d\pi}{dq_s^{PS}} = \frac{\partial \pi}{\partial q_s^{PS}} + \frac{\partial \pi}{\partial p^*}\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} \tag{5}$$

Partially solving (4) and (5) allows us to derive conditions for each of them to occur. In (6) and (7) the generally formulated left hand sides state that, for example, if the total effect of additional market demand on the profit is positive, i.e. if $\frac{d\pi}{dq_d^{PS}} > 0$, then the prosumer should demand as much as he can: Q_d^{PS}. This is then spelled out on the right hand sides of the same lines. Regarding the optimal amount to demand on the market, we see in the first line in (6) that if the market clearing price including transaction fees and also including the positive effect of market demand on the price is still strictly smaller than the prosumer's production costs, the prosumer should demand as much as possible. In other words, using own production capacity for self-supply is more expensive than purchasing on the market. The third line, on the other hand, says that if the prosumer's market demand raises the market clearing price including transaction fees to a level above his production costs c^{PS} – or if the price is too high even without the prosumer's demand – the prosumer will use all of his production capacity for self-supply. Should this capacity be sufficient to cover the prosumer's demand, i.e. $Q_s^{PS} \geqslant Q_d^{PS}$, market demand will be 0; otherwise the remaining demand must still be purchased on the market. The same logic applies for the optimal amount to sell on the market stated in (7). The additional constraint that part of production capacity may be bound by using it for self-supply is captured by $Q_s^{PS} - Q_d^{PS} + q_d^{*,PS}$. This formulation also means that the prosumer favors self-supply over purchasing on the market due to transaction costs. The letters X and Y stand for the isolated decision variable derived from setting the respective total derivatives $\frac{d\pi}{dq_d^{PS}}$ and $\frac{d\pi}{dq_s^{PS}}$ to 0 (see Appendix A).

$$(6)\quad q_d^{*,PS} = \begin{cases} \max \quad \text{if}\, \dfrac{d\pi}{dq_d^{PS}} > 0 \;\Rightarrow\; Q_d^{PS} & \text{if}\, p^* + \tau + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \alpha}\dfrac{\partial \alpha}{\partial q_d^{PS}} < c^{PS} \\ Y \quad \text{if}\, \dfrac{d\pi}{dq_d^{PS}} = 0 \;\Rightarrow\; Y & \text{if}\, p^* + \tau + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \alpha}\dfrac{\partial \alpha}{\partial q_d^{PS}} = c^{PS} \\ \min \quad \text{if}\, \dfrac{d\pi}{dq_d^{PS}} < 0 \;\Rightarrow\; max(0, Q_d^{PS} - Q_s^{PS}) & \text{if}\, p^* + \tau + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \alpha}\dfrac{\partial \alpha}{\partial q_d^{PS}} > c^{PS} \end{cases}$$

$$(7)\quad q_s^{*,PS} = \begin{cases} \max \quad \text{if}\, \dfrac{d\pi}{dq_s^{PS}} > 0 \;\Rightarrow\; Q_s^{PS} - Q_d^{PS} + q_d^{*,PS} & \text{if}\, p^* + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \beta}\dfrac{\partial \beta}{\partial q_s^{PS}} > c^{PS} \\ X \quad \text{if}\, \dfrac{d\pi}{dq_s^{PS}} = 0 \;\Rightarrow\; X & \text{if}\, p^* + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \beta}\dfrac{\partial \beta}{\partial q_s^{PS}} = c^{PS} \\ \min \quad \text{if}\, \dfrac{d\pi}{dq_s^{PS}} < 0 \;\Rightarrow\; 0 & \text{if}\, p^* + \dfrac{\partial \pi}{\partial p^*}\dfrac{\partial p^*}{\partial \beta}\dfrac{\partial \beta}{\partial q_s^{PS}} < c^{PS} \end{cases}$$

The optimal decisions for $q_d^{*,PS}$ and $q_s^{*,PS}$ can be described using a case distinction (see (6) and (7)) that is based on the signs of the total derivatives of (4) and (5). Conveniently, this allows us to uniquely describe 9 different attainable market equilibria which we already graphically described in Figure 2 above and which we summarize in Table I. Again, there are the 4 "corner cases" A-D, the lines connecting and confining the feasible set, e.g. $\overline{BC}$, as well as the "interior" solution ABCD describing the area between.

Table I

Comparison of Optimal Decisions: 9 Cases

	$\frac{d\pi}{dq_d^{PS}}$	< 0	$= 0$	> 0
	> 0	B	$\overline{BC}$	C
$\frac{d\pi}{dq_s^{PS}}$	$= 0$	$\overline{AB}$	ABCD	$\overline{CD}$
	< 0	A	$\overline{AD}$	D

We further proceed by combining the results of (6) and (7) according to Table I. We know, for example, that in Case A the prosumer uses all of his production capacity for self-supply and does not offer any excess production on the market (assuming that his production capacity is larger than his demand). This translates to $q_d^{PS} = 0$ and $q_s^{PS} = 0$. Plugging this into the partially solved total derivatives, the first equation or inequality in each case is derived from $\frac{d\pi}{dq_d^{PS}}$; the second is derived from $\frac{d\pi}{dq_s^{PS}}$. As we defined $\alpha = \frac{q_d^{PS}}{Q_d^{market}}$ and $\beta = \frac{q_s^{PS}}{Q_s^{market}}$ the indirect effect of a decision variable on the market clearing price conveniently vanishes when the according decision variable in the numerator is chosen as 0. In other words, the variable does not influence the market clearing price.

Case A – Lone Wolf: $q_d^{PS} = 0 \quad \wedge \quad q_s^{PS} = 0$

(8) $$p^* + \tau > c^{PS}$$

(9) $$p^* < c^{PS}$$

Assuming $Q_s^{PS} > Q_d^{PS}$, this first case can be used as a baseline: the prosumer is not present at the market at all, hence “lone wolf”. This situation can occur when the market clearing price is smaller than the prosumer’s production costs (9) and the transaction costs τ suffice to invert this inequality (8), in other words, when the production costs lie between the wholesale and the retail price. Combining both inequalities yields the simple result: $\tau > 0$.

Case B – Pure Monopolist: $\quad q_d^{PS} = 0 \quad \wedge \quad q_s^{PS} = Q_s^{PS} - Q_d^{PS}$

$$p^* + \tau > c^{PS} \tag{10}$$

$$p^* + (Q_s^{PS} - Q_d^{PS})\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} > c^{PS} \tag{11}$$

Again assuming $Q_s^{PS} > Q_d^{PS}$, $q_d^{PS} = 0$ and the bracketed term in (11) reduces to ($q_s^{PS} = Q_s^{PS} - Q_d^{PS}$) which means that the indirect effect remains negative. These two inequalities state that for the prosumer to be pure monopolist, first, the retail price is higher than the production costs, and second, that the same holds when the price is reduced by the residual production quantity.

Case C – Standard Market Participant: $\quad q_d^{PS} = Q_d^{PS} \quad \wedge \quad q_s^{PS} = Q_s^{PS}$

$$p^* + \tau + (Q_d^{PS} - Q_s^{PS})\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} < c^{PS} \tag{12}$$

$$p^* - (Q_d^{PS} - Q_s^{PS})\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} > c^{PS} \tag{13}$$

Combining the inequalities yields the following inequality (14) where three main determinants remain: the sign of the bracketed term which depends on whether production capacity is larger than the prosumer’s demand or not; the signs and the size of the effects of both decision variables on the price; as well as the existence of transaction costs.

$$\tau < (Q_s^{PS} - Q_d^{PS})\left(\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} + \frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}}\right) \tag{14}$$

Case D – Pure Monopsonist: $\quad q_d^{PS} = Q_d^{PS} \quad \wedge \quad q_s^{PS} = 0$

$$p^* + \tau + Q_d^{PS}\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} < c^{PS} \tag{15}$$

$$p^* < c^{PS} \tag{16}$$

Here we see in both inequalities, that the price remains below the production costs, even if it is increased by the effect of q_d^{PS}. Hence, it is intuitive, that the prosumer does not make use of his production capacity.

Case AB – Strategic Monopolist: $q_d^{PS} = 0 \quad \wedge \quad q_s^{PS} = X$

$$p^* + \tau > c^{PS} \tag{17}$$

$$p^* + X\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} = c^{PS} \tag{18}$$

For the sake of analysis we again assume $Q_s^{PS} > Q_d^{PS}$. Inequality (17) states that the retail price is higher than the production costs. However, according to (18) the prosumer can strategically reduce the price to such a degree that it equals his production costs. Any further reduction would reduce his profits. Combining the statements yields the following additional result:

$$\tau > X\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} \tag{19}$$

Case AD – Strategic Monopsonist: $q_d^{PS} = Y \quad \wedge \quad q_s^{PS} = 0$

$$p^* + \tau + Y\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} = c^{PS} \tag{20}$$

$$p^* < c^{PS} \tag{21}$$

Inequality (20) shows that the prosumer can strategically increase the price to match exactly his production costs plus transaction costs. Without the indirect effect the price would remain below the costs. Combining the results again shows that the indirect effect must again be lower than the transaction costs in this case:

$$\tau > -Y\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} \tag{22}$$

Case BC – Partial Demander: $q_d^{PS} = Y \quad \wedge \quad q_s^{PS} = Q_s^{PS} - Q_d^{PS} + Y$

$$p^* + \tau - (Q_s^{PS} - Q_d^{PS})\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} = c^{PS} \tag{23}$$

$$p^* + (Q_s^{PS} - Q_d^{PS})\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} > c^{PS} \tag{24}$$

Combining both statements again yields the additional characteristic result:

$$(Q_s^{PS} - Q_d^{PS})\left(\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} + \frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}}\right) > \tau \tag{25}$$

Case CD – Partial Supplier: $q_d^{PS} = Q_d^{PS} \quad \wedge \quad q_s^{PS} = X$

$$p^* + \tau - (X - Q_d^{PS})\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} < c^{PS} \tag{26}$$

$$p^* + (X - Q_d^{PS})\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} = c^{PS} \tag{27}$$

The combination of both statements yields:

$$(X - Q_d^{PS})\left(\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}}\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}}\right) > \tau \tag{28}$$

Case ABCD – Partial Demander and Supplier: $q_d^{PS} = Y \quad \wedge \quad q_s^{PS} = X$

$$p^* + \tau - (X - Y)\frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}} = c^{PS} \tag{29}$$

$$p^* + (X - Y)\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} = c^{PS} \tag{30}$$

Combining the equations shows that in this case the indirect effect of q_s^{PS} plus the indirect effect of q_d^{PS}, multiplied by the difference of decision variables, equals the transaction costs:

$$(X - Y)\left(\frac{\partial p^*}{\partial \beta}\frac{\partial \beta}{\partial q_s^{PS}} + \frac{\partial p^*}{\partial \alpha}\frac{\partial \alpha}{\partial q_d^{PS}}\right) = \tau \tag{31}$$

The results for the 9 cases above show that active prosumption, i.e. actively and strategically choosing market demand and market production, depends on three relations: first, on the relation of market clearing price (including transaction costs) and production costs, i.e. of p^*, τ, and c^{PS}, the latter mainly being determined by the prosumer's choice of production technology; second, on the size of the indirect effect of the prosumer's decision variables on the market clearing price, i.e. on the demand and supply elasticities; and third, on the characteristics of the prosumer, like e.g. the relative size of his demand to production capacity as well as his size compared to the rest of the market. An immediate conclusion is that the different situations outlined above will occur only when the market clearing price and production costs are close. We already see this in Figure 2 as the prosumer's production costs c^{PS} must lie somewhere within the window of attainable market clearing prices; this is especially true when the prosumer is only a small agent, since the effect of the decision variables on the market clearing price are limited by the production capacity and by the prosumer's demand and this window must necessarily remain small. However, aggregating multiple prosumers by centrally controlling their demand and supply increases the size of this active market participant as well as the opportunity to actively adapt to any market environment. Analyzing the cases and the according conditions yields information on the interaction between a prosumer and his market environment. Hence, by simulating certain market situations or by using real data we are able to predict the prosumer's behavior as well as the market outcome.

II(iii). Constrained Optimization

In the previous part we saw that the optimal choice of one decision variable also depends on and interacts with the other; in addition, capacity constraints only implicitly played a role for analyzing the different cases and possible outcomes. These issues suggest using an approach which allows for simultaneously solving the optimization. The objective function remains the same as above (see (1)) and the necessary constraints are stated in (32) and (33) below. Delays or costs for starting the production unit or for increasing or decreasing supply are not included as we assume them to be included in the production costs denoted by c^{PS}.

(32) $$Q_s^{PS} \geqslant q_s^{PS} + Q_d^{PS} - q_d^{PS}$$

(33) $$Q_s^{market} + q_s^{PS} - Q_d^{market} - q_d^{PS} \geqslant 0$$

(34) nonnegativity for decision variables and Lagrange multipliers

The first constraint (32) states that the prosumer cannot produce more than his own production capacity. It also implicitly contains the constraint that he can only use a maximum of Q_s^{PS} for self-supply; also, both cases production capacity being larger than the prosumer's demand and vice versa, i.e. $Q_s^{PS} > Q_d^{PS}$ as well as $Q_s^{PS} < Q_d^{PS}$ are considered. The former is straightforward; the latter simply requires the prosumer's market demand q_d^{PS} to be larger than 0. Lastly, since equality is not demanded, it is also possible to withhold supply capacity from the market and not use it at all. The constraint in (33) covers the idea that the prosumer's demand cannot remain unfulfilled at any time. I.e. if the available production capacity on the market Q_s^{market} were too small, then the prosumer must use his own production capacity to offer on the market in order to be able to also purchase on the market. This accounts e.g. for situations whenever transaction costs prevent the exchange of goods and hence the functioning of the market leading to a decoupling of market zones and differing market clearing prices e.g. across regions. Examples are so called load pockets that may occur due to transmission congestion in electricity markets based on nodal pricing mechanisms. Nonnegativity of q_d^{PS} requires that that the prosumer cannot artificially raise the market clearing price and then balance it with non-existent production capacity, thereby profiting from an artificially high market clearing price.

In the next step we set up the Lagrangian and derive the according Karush-Kuhn-Tucker conditions in order to solve the resulting equation system for the optimal solution. Since the constraints are linear and the objective function is quadratic, the conditions for a unique solution are necessary and sufficient. An initial analysis based on several examples allows us to get an idea on how the simulation results of Section III are going to look like. Figure 3 depicts the prosumer's optimal decision variables depending on the size of the total market demand Q_d^{market}, ceteris paribus – in particular the prosumer's production costs c^{PS} –

with the prosumer's production capacity being twice the size of his demand and q_{own}^{PS} again denoting the amount of production capacity needed for self-supply, i.e. $Q_d^{PS} - q_d^{PS}$. Low values of total market demand indicate a low market price which induces the prosumer to not use his production capacity at all and to purchase all of his demand on the market; a large size of total market demand, on the other hand, leads to a high market price and the prosumer optimally decides to produce as much as he can for self-supply, i.e. $q_d^{PS} = 0$, and to offer the remaining capacity on the market. The plateaus at A and B are attained when the prosumer's demand is fulfilled and the production capacity constraint is reached, respectively. We find that only 5 of the 9 cases that presented in Section II(ii). seem to be relevant; moreover, the prosumer never demands from and supplies to the market at the same time. I.e. we find a "movement" of the market equilibrium along the border of the feasible region shown above in Figure 2. This result is, however, only attained by varying one single input variable of the optimization, Q_d^{market}, and does not cover the whole range of possible combinations of demand and supply elasticities as well as prosumer's market sizes which we found to be relevant to describe each of the 9 possible cases of Table I above.

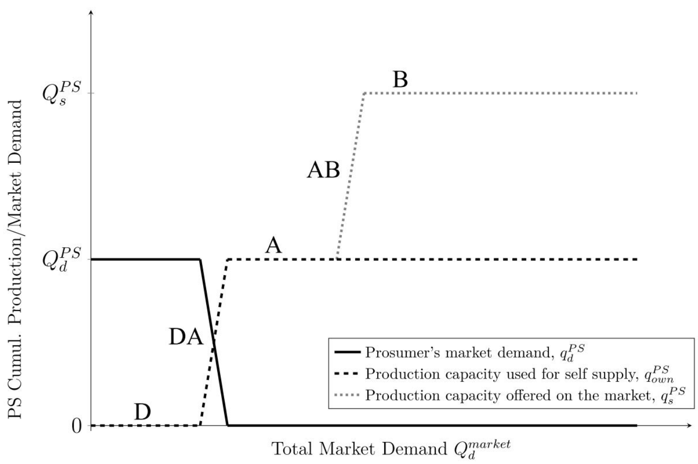


Figure 3: Profit Maximizing PS Bids with Changing Total Market Demand

II(iv). Comparison to Passive Prosumption

Up to this point we were able to show how the prosumer would behave optimally to maximize profits which is equivalent to minimizing costs. However, the initial idea for this paper was based on the notion that there actually is an incentive for the prosumer to start behaving actively and strategically, i.e. that there is a profit advantage compared to other forms of market participation. Therefore, we first look at what "normal" market participants would do: assume again that an agent does own production capacity which may be used for self-supply or offered on the market. This agent also affects the market clearing price but he does not actively incorporate this effect for his choice, i.e. the only "strategic" action is to compare market price and production costs and decide in each period whether to produce or not, and to cover his demand on the market in the latter case. This is at the same time easy to understand and to implement, which is why this is e.g. the common form of prosumption in electricity markets where small, decentralized prosumers usually still have an according contract with their electricity provider or load serving entity (see Section I). We can also find this behavior in Figure 2 and in the case distinction in Table I: this prosumer either does not make use of any production capacity and remains a pure consumer – as in Case D – or the prosumer satisfies all of his demand using own production and offers any excess production on the market – as in Case B. We refer to this reduced behavior as "passive prosumption".

The objective function for this passive prosumer is based on comparing the following two profits and choosing the larger one:

$$\pi^D = -(p^* + \tau)(q_d^{PS}) \tag{35}$$

$$\pi^B = p^*(q_s^{PS}) - c^{PS}(q_s^{PS} + Q_d^{PS}) \tag{36}$$

Figure 4 depicts the different profits of different kinds of market participants when the size of total market demand Q_d^{market} changes, ceteris paribus. Note that the profits are always negative as we actually consider a cost minimization problem where the utility of consumption is assumed to be constant (see Section II(ii).). The dashed and the dot-dashed black lines show the profits of the pure consumer and the excess producer, respectively. The market clearing price rises as total market demand is increased; this is beneficial for the excess producer, but vice versa for the pure consumer. At the intersection of these two profit functions the market price equals the prosumer's production costs which induces a change of strategy as total market demand increases. The dashed gray line depicts the profit in Case A, i.e. of a prosumer who is completely self sufficient, who does not participate in the market, and who is thus not affected by changes in the market. We do not include this behavior in our definition of passive prosumption as it would seem counter-intuitive to not use excess production capacity when price taking is assumed. An active prosumer, on the other hand, should include this option and, as we can see with the black line, he will also do so. The dotted gray line shows that Case C of simple market participation is always inferior to other cases in this particular scenario. The difference in profits between Case B and Case C is mainly due to additional transaction costs for buying on the market. In addition to active prosumption just being the upper envelope of the different strategies, we also see the prosumer taking the indirect effect of q_d^{PS} and q_s^{PS} on the market clearing price into account, i.e. the effect of relaxing the price taking assumption: The two shaded areas depict the profits of the strategic Cases AD and AB, respectively. To summarize, the profit advantage of active compared to passive prosumption does exist and is based on two parts: first, on not participating in the market at all (Case A), and second, on the incorporation of price effects when choosing the decision variables (Cases AD and AB). Active prosumption weakly dominates passive prosumption.

III Empirical Study

The findings in the previous section are the general effects of prosumer behavior in a market environment. To complement these general results, we illustrate prosumer behavior in an empirical study. Due to the lack of data on actual prosumers in real markets we simulate prosumer behavior in an electricity market. We use the German-Austrian day-ahead spot market operated by EPEXSpot because the necessary data on the market characteristics are available, i.e. hourly market clearing prices and quantities as well as all underlying hourly

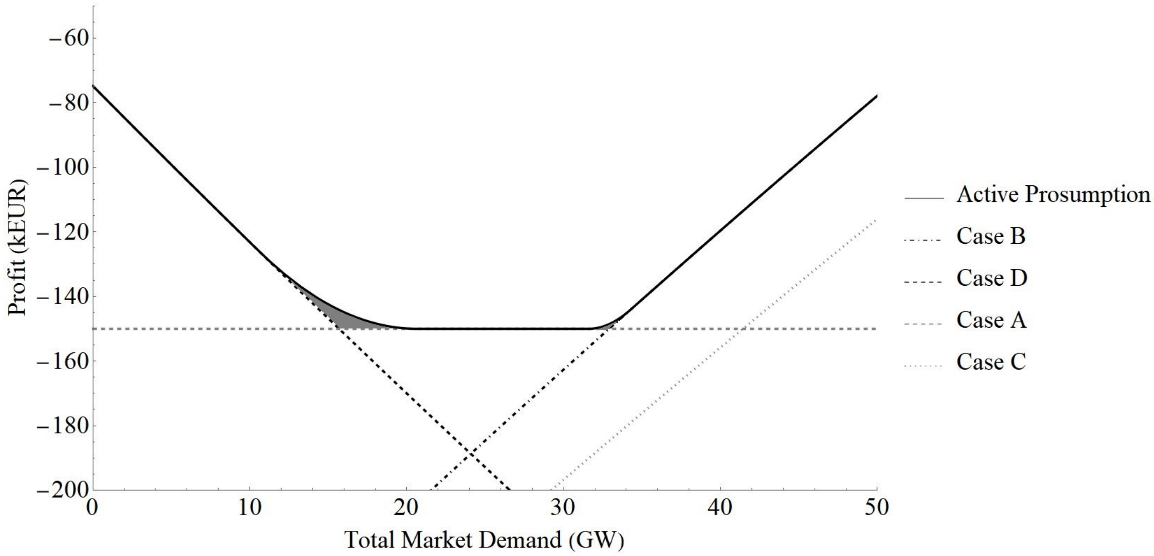


Figure 4: Profit Comparison with Changing Total Market Demand Q_d^{market}

price-quantity bids – that is the entire step functions – separately for demand and supply. As we stated in Section I, in addition the role of prosumers in the German electricity market is an ongoing debate. Several studies on prosumers in German electricity markets e.g. focus on technology adoption preferences (Schill et al. 2017) or on storage with systems perspective (Ottesen et al. 2016), but they do not take price elasticities into account. In contrast to these studies, we analyze the relationship between price elasticities in different demand situations and the role of the prosumer's size. We derive 6 typical days and their corresponding 24 hours based on market data for the years 2014 to 2016. For each of these 144 situations (6 days times 24 hours) we investigate how an additional market participant with prosumer characteristics behaves and how this influences the market results.

III(i). Model Calibration and Scenario Definition

The necessary data for an application of our modeling framework can be derived from the formal description of the demand and supply functions in Section II, Equations (2) and (3): first, the demand and supply elasticities to calculate the slopes of the demand and supply functions (see Appendix C); and second, a representative point of the demand and supply function to calculate the intercepts; for the latter we choose the equilibrium price and quantity. The next subsection contains the description of the empirical estimation of these elasticities. Then, to model the influence of an additional prosumer, we define various scenarios based on the prosumer's production capacity, his production costs, and his demand. Finally, we assume transaction costs τ to be 1.5 EUR/MWh and a fixed total market supply of 80,000 MW.

III(i).i Estimation of Demand and Supply Functions

For the estimation of the price elasticities for demand and supply we choose a state of the art framework by Bigerna & Bollino (2014) to estimate the following hourly simultaneous equations system as a seemingly unrelated equations regression model both for demand (37) and supply (38). Here, d_i is a dummy for typical situations for which we choose the following six: summer season (SU), winter season (WI), the remaining "transition seasons" (TS), for both a working day (Work) and a weekend day (Wend). We include each hourly demand and supply step function with 100 representative bids for the 24 hours of a working day and a weekend day for each of the 36 months of 2014 to 2016; thus, our sample consists of 172,800 observations (36 months times 2 days times 24 hours times 100 bids). Based on the estimation equations (37) and (38) we can calculate the elasticities for our model (see (39) and (40)).

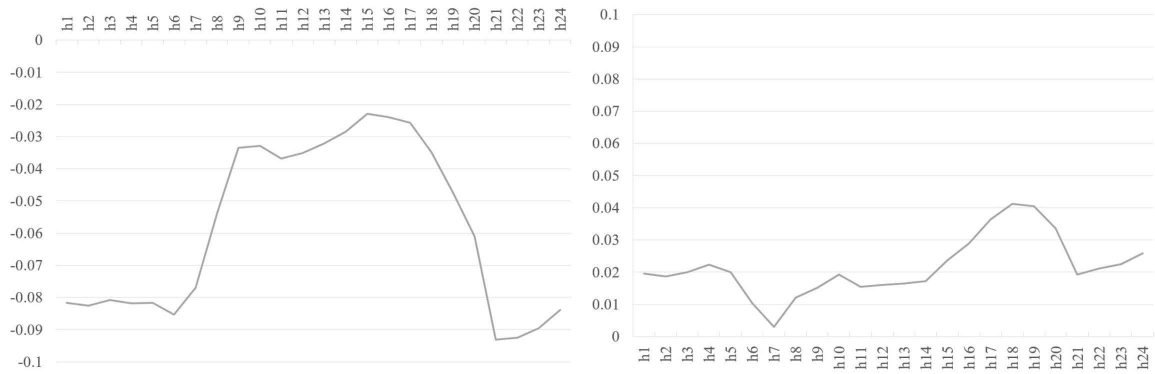
$$ln(dem_h) = \alpha_h ln(p_h) + \sum_i \beta_{i,h} d_i * ln(p_h) \tag{37}$$

$$ln(sup_h) = \alpha_h ln(p_h) + \sum_i \beta_{i,h} d_i * ln(p_h) \tag{38}$$

$$\frac{\partial dem_h}{\partial p_h} = \alpha_h + \sum_i \beta_{i,h} d_i \tag{39}$$

$$\frac{\partial sup_h}{\partial p_h} = \alpha_h + \sum_i \beta_{i,h} d_i \tag{40}$$

Figure 5 illustrates the demand and supply elasticities for the case of a summer working day (SU/Work). We see that a 1% price increase would decrease demand in the evening and night hours by about 0.08% which is almost three times as much as during daytime. The price elasticity of supply, on the other hand, is more balanced with a very inelastic morning low of only 0.003 and an evening peak where supply is increased by 0.04% for a 1% increase in prices. These elasticities play an important role for determining the prosumer's optimal decisions – as we also show in the Cases in Section II(ii). – since they determine the "size" of the window of attainable market clearing prices (see Figure 2). The elasticities of a summer working day indicate that this window is largest in terms of prices during daytime, and in particular in the hours 9 to 14. Tables containing all supply and demand elasticities for the 6 typical days can be found in Appendix B



(a) (b)

Figure 5: Estimation Results for Price Elasticities (SU/Work): (a) Demand Elasticities, (b) Supply Elasticities

III(i).ii Scenario Definition

We use the estimation results from above as well as market data to analyze the relationship between price elasticities in different market situations and the role of prosumer size. Therefore, we will first define a base scenario followed by different variations from the base scenario that we take into account. For all scenarios we assume the prosumer's hourly demand to follow the pattern of the market by assigning to him 1% of overall hourly market clearing quantities; i.e. for an hour with e.g. 40,000 MW sold on the market, the prosumer's demand is 400 MW. The prosumer's average demand is approximately 550 MW, with a minimum at 375 MW and a maximum at 753 MW.

- **Base Scenario**

  Figure 6 shows the development of the market prices and quantities in the 144 typical hours. In the base scenario we assume that the production capacity of the prosumer is close to his average hourly consumption, that is about 600 MW; and the production costs are assumed to be close to the average market price of about 30 EUR/MWh.

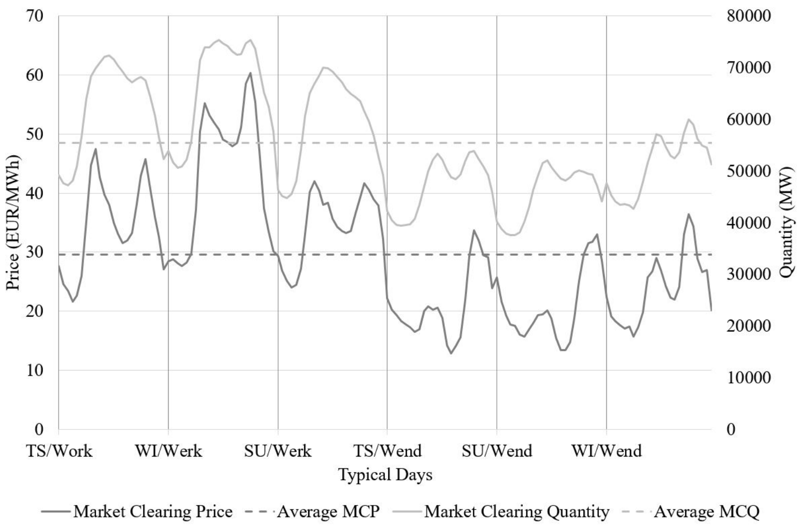


Figure 6: Market Prices and Corresponding Volumes for the Typical Days

- **Variations from Base Scenario**

  To get a better understanding of the relationship between prosumer size and costs and optimal market behavior we want to vary on the one hand the production capacity of the prosumer and on the other hand the production costs. For the capacity we choose in addition different cases of capacity around the maximum hourly consumption and minimum hourly consumption. For the production costs we choose overall five scenarios: 10 EUR/MWh and 20 EUR/MWh higher and lower than the average market price of about 30 EUR/MWh. This is in the range of expected levelized cost of energy for decentralized generation (see Comello & Reichelstein 2016).

With this information we can determine for every typical day and the corresponding hours the optimal behavior of the prosumer, the corresponding "new" market price, and the profit advantage compared to passive prosumption.

III(ii). Results

For each of these 30 scenarios we derived the prosumer's optimal market behavior, i.e. market production, market demand and self-supply. Figure 14 in Appendix D contains these optimal values for all 4,320 typical hours (6 days times 24 hours times 30 scenarios). Here, we present one exemplary scenario, viz. 1200/10, in Figure 7 where the x-axis depicts the 6 typical days with their 144 hours. In most of the hours, self-supply and market production are equal to the prosumer's production capacity, Q_s^{PS}, i.e. no capacity remains unused. The prosumer does not cover his demand Q_d^{PS} on the market and is thus a Pure Monopolist as we defined in Case B. The market clearing price is mostly higher than the prosumer's production costs of 10 EUR/MWh (see Figure 6); however, when these values are close, in particular in TS/Wend and SU/Wend, we observe that the prosumer acts as a Standard Market Participant (Case C) selling all of his production capacity on the market and at the same time covering all of his demand on the same market. Surprisingly, maximally decreasing the market clearing price with supply and increasing it at the same time with demand seems to be optimally in the end. This example highlights that the prosumer's decisions not only depend on his own characteristics, i.e. production costs and capacity as well as demand, but also on the market environment via different hourly demand and supply elasticities and market clearing prices. It is, however, not clear which effect or relation is most influential. Lastly, we also observe a negative spike of market production during a few hours in TS/Wend; self-supply and market production do not add up to production capacity indicating that the prosumer withholds capacity from the market, i.e. acts as a Partial Supplier (Case CD).

Including again all 4,320 observations hours, we proceed by classifying the results according to the cases described in Section II(ii). above and by deriving their distribution. Figure 8 shows the frequency of the different outcomes. Part (a) on the left depicts the distribution of cases for different production capacities, whereas Part (b) on the right shows the distributions for different prosumer's production costs. The values of the former are derived by calculating e.g. for all 5 scenarios containing 200 MW of production capacity the average frequency each case occurs. E.g. Case B occurred in all 6 different capacity scenarios on average 83 times.

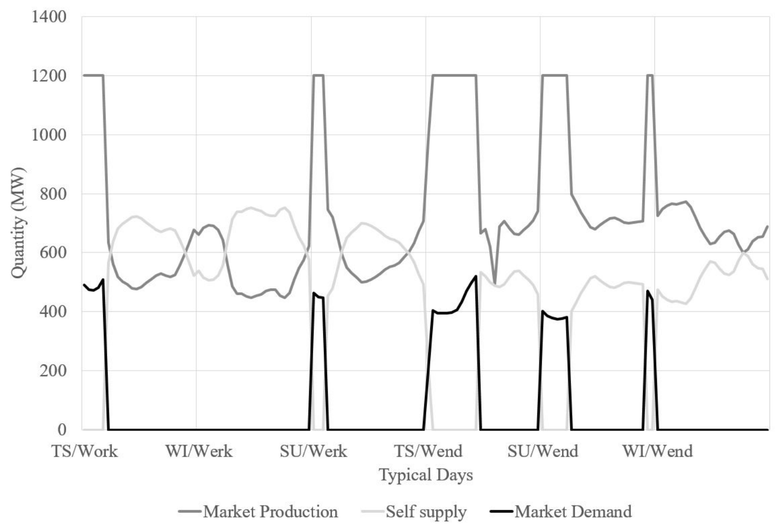
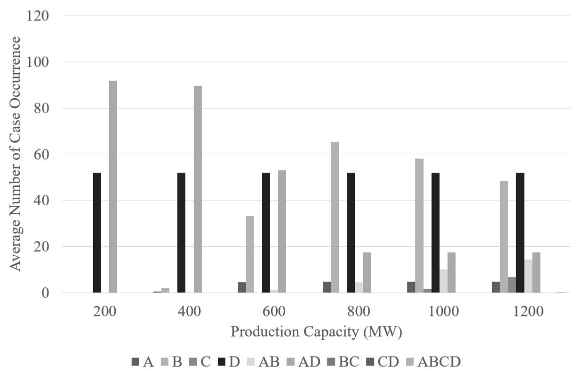
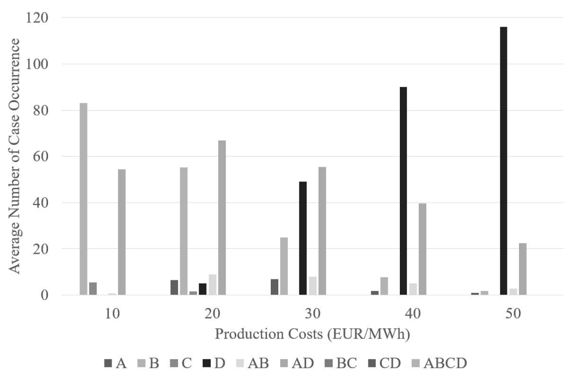


Figure 7: Optimal Prosumer Decisions for Production Capacity of 1200 MW and Production Costs of 10 EUR/MWh

This is done to eliminate the fourth dimension of costs and we used the same procedure for Part (b) accordingly. Overall, Cases B (Pure Monopolist), AD (Strategic Monopsonist), and D (Pure Monopsonist) are the most relevant ones. Part (a) indicates that choosing Case D, i.e. being a simple consumer, is insensitive to changing production capacity. Cases B and Case AD, on the other hand, depend strongly on the size of capacity, with the incidence of the latter decreasing, and the former showing a maximum at 800 MW. We also see that additional production capacity induces the prosumer to choose between more strategic cases – 2 Cases vs. 7 Cases – because the window of attainable market clearing prices (see Figure 2) is increased. Being able to choose only Case B or Case D is not different from being a passive prosumer, i.e. just a small amount of production capacity does not seem to yield any profit advantage at the first glance. In Part (b) the amount of each case appearing varies strongly with a transition of Case B to D as costs are higher and the number of hours where costs are larger than the market clearing price increases; i.e. the prosumer has fewer opportunities to profitably produce for the market and switches to be a simple consumer.



(a)



(b)

Figure 8: Equilibrium Outcomes According to (a) Production Capacity and (b) Production Costs

III(ii).i General Analysis of Active Prosumption

As a first step to analyze the different effects in detail, Figure 9 gives the average impact of active prosumption on the market clearing price. This is calculated as the difference of the market clearing price including and the price excluding the prosumer. We see that with small prosumers, the new market price will always be higher than before as their production capacity does not suffice to cover their market demand. This leads to an excess market demand situation driving prices up. The slight kink e.g. in the graph for costs of 50 EUR/MWh at a capacity of 800 MW indicates that higher production costs prove to be a "natural" barrier preventing the prosumer to further decrease the market clearing price by e.g. starting to withhold capacity. With low production costs of e.g. 10 EUR/MWh this barrier is not binding and the final market clearing price will even be lower in the optimum; this is relevant for capacities larger than 600 MW in our empirical study.

The development of the prosumer's market demand and market production (y-axis) for different production capacities (x-axis) and different production costs is shown in Figure 10. The values are summed quantities of the 144 typical hours within one scenario. Given his own production capacity the prosumer will increasingly sell to the market when his capacity

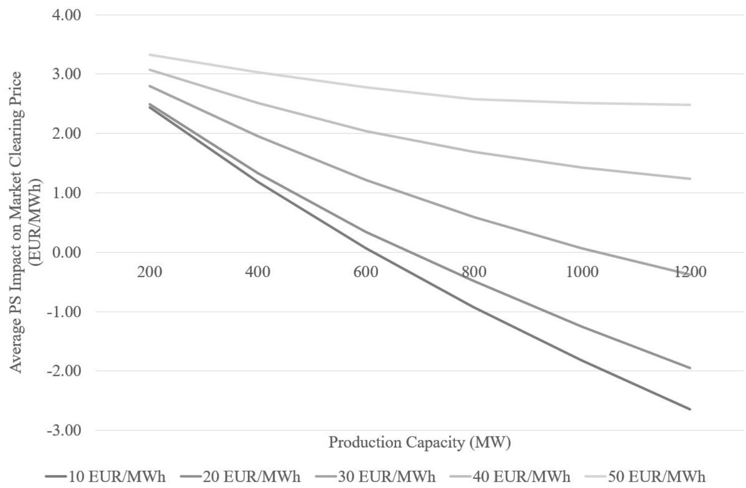
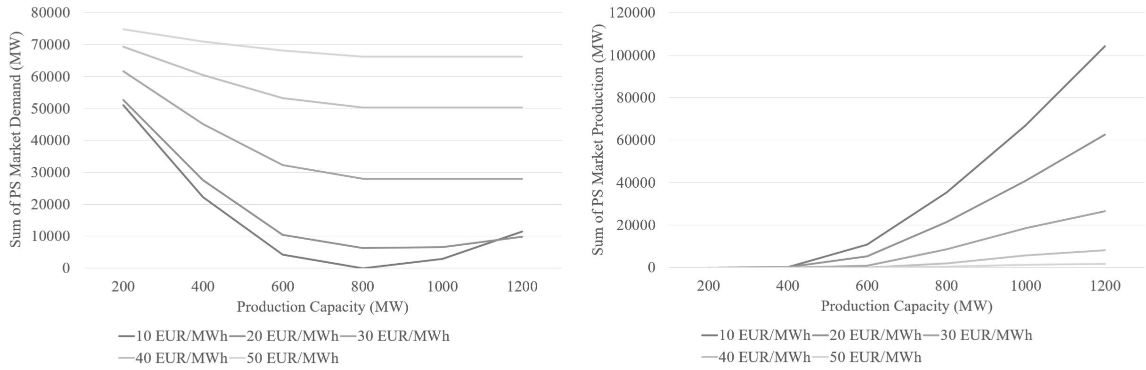


Figure 9: Average Impact on Market Clearing Price

increases. However, increasing the prosumer's capacity relative to the total market supply also leads to a decreasing market price which at the same time increases the prosumer's market demand. This can be seen in the graphs for costs of 10 and 20 EUR/MWh in Part (a) – with the additional influence of the "outliers" of Cases C which we find in scenarios 1000/10, 1000/20, 1200/10, and 1200/20. For higher prosumer's production costs this effect is not likely to occur because of lacking competitiveness relative to the market. This is also shown by the flat market production graphs for costs of 40 and 50 EUR/MWh in Part (b); and by the flat parts of the top cost graphs in Part (a).

The observation from above, viz. that increasing production capacity leads to increased market production, can also be visualized by plotting the ratio of residual production capacity to total market supply, $(Q_d^{PS} - Q_s^{PS})/{-Q_s^{market}}$, against the derived optimal market production for all 4,320 observations (see Figure 11). Depending on the scenario, this ratio will be negative if the prosumer's hourly demand is larger than his production capacity; and as we can see on the left side in Figure 11 the prosumer will never choose to sell any production on the market. This ratio turns positive, on the other hand, when the prosumer's production capacity is larger than demand. I.e. the prosumer will only start to participate on the supply side of the market if he owns a minimum amount of production capacity that additionally



(a) (b)

Figure 10: (a) Market Demand and (b) Market Production for Different PS Production Costs and Production Capacities

exceeds his demand with the plot indicating a linear positive relationship. We can also see the different strategic cases of the prosumer: the Cases B and D determine the outer borders of this triangular shape; the observations in between are cases where the prosumer e.g. decides to withhold capacity, like in Case AB. And the outliers where the prosumer offers 1000 or 1200 MW on the market are the instances of Case C.

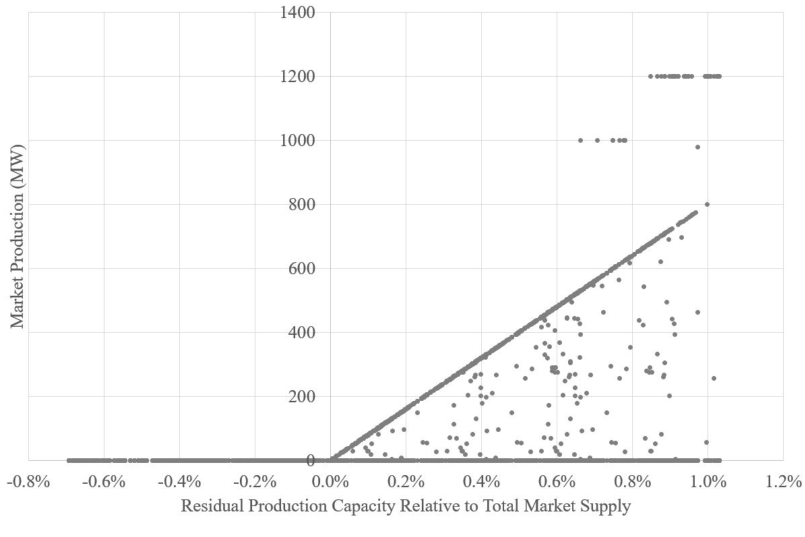
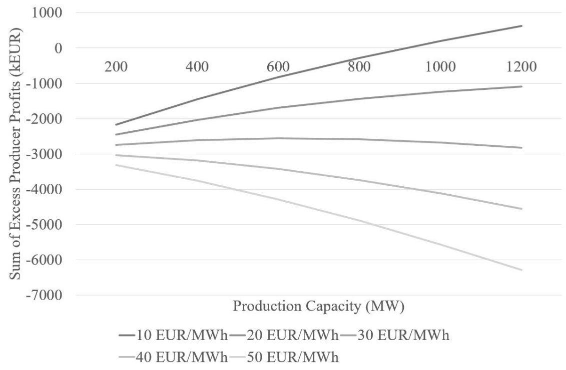


Figure 11: Interdependence of Available Production Capacity and Market Production

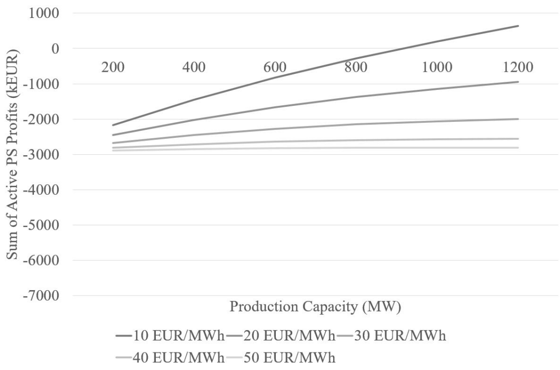
III(ii).ii Profit Advantage of Active Prosumption

One of the results of Section II was that active prosumption is a weakly dominating strategy and that the profit advantage depends on the relation of productions costs to market clearing price, on the supply and demand elasticities, and on the relative size of the prosumer. Based on our empirical study we can show this in more detail. Figure 12 shows the profits of an excess producer, i.e. a Pure Monopolist (Case B) and of an active prosumer for all levels of production capacity and differentiated according to production costs. The values are derived by summing up all profits of the 144 typical hours. As capacity increases there are more and more incidents where the prosumer can be 100% self sufficient and where excess production will decrease the market clearing price. Part (a) shows that the Pure Monopolist's profit can even decline with increasing production costs because the excess production will even push prices below costs; at some point, of course, this Pure Monopolist should choose to become a simple consumer, i.e. a Pure Monopsonist (Case D). An active prosumer, on the other hand, can prevent this by actively adjusting and reacting to the market environment e.g. by withholding capacity from the market. Again, the profits are negative because we do not take the utility of demand into account; thus the advantage of active prosumption consists of restricting losses. In addition, we see the stated weak dominance in Part (b) for example for costs of 20 EUR/MWh because profits are equal at low capacities, but when production capacity increases, the active prosumer even has an additional advantage (see also Figure 11 above).

In the final Figure 13 we plot the absolute hourly profit advantages of active prosumption for all 4,320 observations; as defined in Section II(iv). the profits of a passive prosumer are calculated by allowing him to choose between excess production or simple consumption, i.e. between Case B and D. We can confirm the analytical result that the advantage is highest when the market clearing price is close to the production costs. The "peak" for costs of 10 EUR/MWh is only small as the distribution is truncated below by the observed market clearing prices in our 144 typical hours with a minimum at 12.84 EUR/MWh. Per unit profit increases range from 0.01 to 0.03 EUR/MWh for the smallest case of 200 MW production



(a)



(b)

Figure 12: Sum of Profits of (a) Pure Monopolist (Case B) and (b) Active Prosumer

capacity and up to 0.03 to 2.52 EUR/MWh for the largest depicted case of 1200 MW production capacity for different cost levels. Extending capacity up to 8700 MW enables the prosumer to raise per unit profits from 9.7 to 13.4 EUR/MWh.

In addition, variance is higher with higher production costs. Since each set of data points for production costs contains all six assumed production capacities, we have to resort to the distribution of strategic cases shown in Part (a) of Figure 8 above for an explanation. There we see that, keeping the costs constant, additional capacity increases the options for a prosumer. Hence, we expect more production capacity to lead to a greater leeway in strategically influencing market outcomes. This is ultimately based on the larger window of attainable market clearing prices (see Figure 2) as production capacity increases. For a more detailed analysis on this, we also calculated our model for a prosumer production capacity of 8700 MW comparing to one of the largest direct sellers at current EPEXSpot, Statkraft. We observe that this higher capacity results in the prosumer playing more the role of a Strategic Monopolist (case AB, 22% of all situations) or a Partial Supplier (case CD, 26% of all situations). The reason for this is that bidding the total capacity into the market would decrease the prices too much and thus decrease own profits. In contrast, the frequency of being residual Pure Monopolist (case B) reduces, which is a consequence of increased market power. The role Pure Monopsonist (case D) is independent of the production capacity and remains at 36% of all situations. Lastly, the position of the peaks also indicates that prosumers with different production technologies and therefore different production costs will be active in different zones of market clearing prices. Hence, active prosumption is a profitable strategy for all market participants who simultaneously demand from and supply to the market.

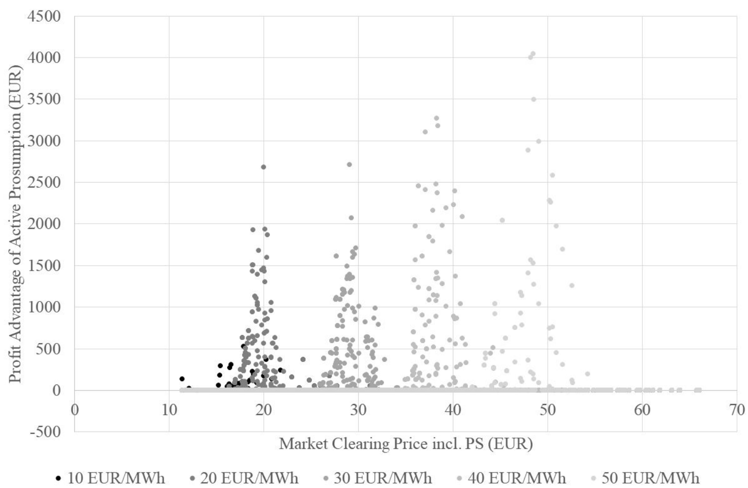


Figure 13: Profit Advantage of Active vs. Passive Prosumption

IV Discussion

The proposed model is based on several important assumptions that need to be taken into account for interpreting the results. First, the prosumer influences the market clearing price by rotating both the demand and supply functions as he chooses the quantities to demand from and supply to the market. We found that assuming a parallel shift does not change the main results of our analysis which differ only in quantitative terms. Second, the demand and supply functions are assumed to be linear, whereas in the EPEXSpot day-ahead electricity market they are highly nonlinear (hockey-stick form) and actually step functions with, on average, 700 steps per hour. We are able to handle this nonlinearity by estimating the elasticities and calculating the slopes at the various market equilibria; incorporating step functions would deprive us of the analytical analysis of an additional prosumer. Third, we also assumed that the prosumer has perfect foresight of and his effect on the market clearing price. Again regarding the electricity market, the forecasts of day-ahead prices are quite accurate and, as we show in Figure 13 in Section III(ii).ii, each distribution of profit advantages covers a range of prices; i.e. it is not necessary to perfectly know the market environment in order to gain an advantage, it suffices to be close enough. And fourth, concerning the profit advantage, we implicitly assume that all the 144 typical hours are equally likely to appear during a year. We could additionally extrapolate these 144 hourly profit advantages to e.g. an assumed typical year. This does, however, not seem meaningful as our model and in particular the production costs are highly simplified and the additional information gained by this exercise is unclear. We do for example not include startup costs after not using or withholding production capacity, or ramp-up/down delays for changing the actual quantity produced which only occur when production capacity is not simply relayed from market to self-supply.

Several issues had to be reserved for future work. As of yet, the prosumer's production capacity is modeled as if it were just one unit with uniform production costs. The natural extension would be to model a portfolio of units with different production costs each, i.e. to a multi-unit commitment problem. Also, since active prosumption leads to a profit advantage, this business model will attract multiple active prosumers. Thus, the model must be generalized to more than one single active prosumer in order to check for interactions or concerted actions between these new market participants. In a next step, it is also important to disentangle the three effects on the prosumer's optimal decision, viz. the relation of (a) market clearing price to production costs, (b) demand and production capacity, and (c) elasticities.

As stated in Section III(i).i above, the elasticities indicate major prosumer action in hours 9-14 because the window of attainable prices is largest; this does, however, not include information on the general price level, i.e. of effect (a). Finding a way to disentangle these effects could indicate hours where we expect an increase of active prosumption. So far, we only observe profit gains when production costs and market clearing prices are sufficiently close (cf. 13). Finally, concerning active prosumption in electricity markets, the model may be extended by including further markets, e.g. balancing market providing flexibility. Prosumption seems to be a simple way to flexibly adapt to the market environment as, in particular, relaying production from the market to self-supply does not involve any physical constraints, but price signals between those markets may differ a lot changing the prosumer's incentives. Second, the results are based on the active prosumer's impact on the market clearing price, which should work even better in markets based on nodal pricing. This is because the relative size of a prosumer as well as his impact on the price is even larger in load pockets which occur due to transmission congestion. By comparison, our empirical study was based on a small prosumer with only 1 % of total market demand and between 0.3 and 1.5 % of total market supply. In a further sensitivity analysis, an increase to roughly 10 % market share already led to tremendous profit gains. And lastly, an extension must focus on giving the prosumer the possibility to intertemporally shift supply and/or demand via storage or flexibility. Even though this is an important and very recent topic in the electricity market – including the new term of "ProSumAge" (see Green & Staffell 2017) – this is also important for other market environments where storing supply is possible, like e.g. for farmers who can feed their cattle or store the grain in silos.

V Conclusion

In this article we address the important issue of consumer market participation when there is the possibility to – at least partially – rely on marketable own production. Theoretical results indicate that the optimal choices of production, sales and sourcing crucially depend on own production costs and capacity as well as own demand relative to market equilibrium. We apply our model to the electricity market. Varying scarcity situations reveal the prosumer to switch strategic roles, from net buyer to net supplier, on an hourly basis. In particular, the prosumer exerts market power in peak as well as off-peak situations. This is in part due to the additional influence on market enabling her to increase market power and to substantially increase profits even with relatively low market shares. In general, these results apply to any market where the same participant is able to simultaneously demand from and offer to a market having an impact on market price. The potential to either increase supply or exert market power demonstrates the ambivalent role a prosumer can take with regard to allocative efficiency. This also holds for other markets than electricity such as transportation (Uber), overnight stays (AirBnB), or car-sharing markets. Further examples are Amazon's or Google's server farms whose processing power may be used for their own tasks or offered to other customers. This has manifold implications for assessing strategic behavior in vertically integrated markets as well as for competition policy and regulation. Regarding electricity markets, active prosumption is a new way for companies to vertically integrate. This "Un-Unbundling" may serve to circumvent regulations and potentially undermine the liberalization of the market.

Notes

[1]E.g. the Big 6 in the UK or the Big 4 in Germany compare to e.g. 150,000 private solar power systems in Finland (TEM 2014) or to 34,000 small scale prosumer systems (including storage) in Germany.

[2] See Selectra (2017), innogy (2017).

[3] It is worth noting that active prosumption differs from other forms of market participation such as shifting demand and/or storage (intertemporal arbitrage, see Crampes & Creti (2006), Ottesen et al. (2016)). There is also the option of virtual bidding, which is a purely financial transaction without the actual risk of operating a generating unit or of needing to cover physical demand. This is usually done to generate arbitrage profits between sequential markets and the transactions must be undone again before actual delivery to or from the virtual bidder takes place (see Jha & Wolak 2015, van Eijkel et al. 2016). We do not address these issues in this article.

[4] An analysis of possible principal-agent issues and of optimal contractual design of this arrangement must be left for future analyses.

[5]This is similar for other markets such as taxi rides (Uber) or overnight stays (AirBnB).

[6]We further assume the consumer to have an inelastic demand, therefore no optimization with respect to consumption takes place.

[7]This cost can also include opportunity cost.

[8]Bessembinder & Lemmon (2006) find local disequilibria to provide another explanation for this phenomenon. Convex cost functions in combination with locally varying demand make it profitable to hedge throughout space and adapt real-time supply and demand locally.

[9]Avenel (2008) investigates the related issue of the optimal degree of vertical integration of a firm in light of technology adoption. In contrast, this article focuses on consumer market participation based on production by new, decentralized technologies.

[10]The prosumer's effect could also be modelled as a parallel shift of both functions. Testing such a model showed, however, that the results differ only in quantitative terms and remain the same regarding the main points we try to make in this paper. The most realistic approach is leaving the functions unaffected up to the "step" the prosumer introduces and introducing a parallel shift. This nonlinearity introduces many equilibria and does again not help us forward our case.

A Equations for X (Optimal q_s^{PS}) and Y (Optimal q_d^{PS})

The optimal hourly quantities the prosumer produces for and demands from the market, i.e. q_s^{PS}) and q_d^{PS}, respectively, are derived based on Equations 4) and (5 (see Section II(ii).). Solving the partial derivatives, setting the resulting total derivative to 0, and isolating the respective decision variables yields the optimal (unconstrained) decision variables stated in the equations below:

$$q_s^{*,PS} = \frac{x\ y}{a_d} - Q_s^{market} - \frac{\sqrt{a_d^2\ (a_d - a_s)\ x\ y\ (a_s - c^{PS})\ (-x\ y\ + a_d\ (q_d^{PS} + Q_s^{market}))}}{a_d^2\ (a_s - c^{PS})}$$

$$q_d^{*,PS} = \frac{a_d\ z}{x} - Q_d^{market} + \frac{\sqrt{a_d\ (a_d - a_s)\ x^2\ z\ (a_d - c^{PS} + \tau)\ (-\ x\ (q_s^{PS} + Q_d^{market})\ + a_d\ z)}}{x^2\ (a_d - c^{PS} + \tau)}$$

where

$$x = a_s - c^{market}$$

$$y = q_d^{PS} + Q_d^{market}$$

$$z = q_s^{PS} + Q_s^{market}$$

B Estimated Demand and Supply Elasticities

Table II

Demand Elasticities for the 24 Hours on the 6 Typical Days

	TS Work	WI Work	SU Work	TS Wend	WI Wend	SU Wend
h1	-0.032	-0.044	-0.082	-0.049	-0.001	-0.059
h2	-0.021	-0.036	-0.083	-0.041	-0.001	-0.050
h3	-0.014	-0.035	-0.081	-0.041	-0.001	-0.045
h4	-0.009	-0.037	-0.082	-0.044	-0.001	-0.044
h5	-0.012	-0.039	-0.082	-0.048	-0.001	-0.044
h6	-0.020	-0.043	-0.085	-0.050	-0.001	-0.054
h7	-0.031	-0.037	-0.077	-0.048	-0.004	-0.068
h8	-0.049	-0.021	-0.054	-0.031	-0.023	-0.078
h9	-0.049	-0.009	-0.033	-0.019	-0.029	-0.071
h10	-0.050	-0.023	-0.033	-0.023	-0.036	-0.063
h11	-0.050	-0.039	-0.037	-0.031	-0.039	-0.058
h12	-0.047	-0.047	-0.035	-0.034	-0.041	-0.053
h13	-0.039	-0.048	-0.032	-0.030	-0.038	-0.045
h14	-0.037	-0.044	-0.028	-0.027	-0.041	-0.042
h15	-0.035	-0.043	-0.023	-0.026	-0.044	-0.037
h16	-0.038	-0.040	-0.024	-0.026	-0.051	-0.034
h17	-0.043	-0.038	-0.026	-0.030	-0.043	-0.039
h18	-0.052	-0.030	-0.035	-0.038	-0.031	-0.060
h19	-0.059	-0.028	-0.047	-0.043	-0.028	-0.079
h20	-0.062	-0.030	-0.061	-0.047	-0.031	-0.092
h21	-0.068	-0.055	-0.093	-0.064	-0.040	-0.099
h22	-0.059	-0.061	-0.092	-0.066	-0.038	-0.088
h23	-0.053	-0.060	-0.090	-0.068	-0.029	-0.077
h24	-0.046	-0.056	-0.084	-0.064	-0.017	-0.064

Table III

Supply Elasticities for the 24 Hours on the 6 Typical Days

	TS Work	WI Work	SU Work	TS Wend	WI Wend	SU Wend
h1	0.057	0.075	0.019	0.067	0.099	0.035
h2	0.058	0.072	0.019	0.066	0.100	0.037
h3	0.058	0.070	0.020	0.064	0.100	0.038
h4	0.058	0.068	0.022	0.059	0.099	0.039
h5	0.059	0.064	0.020	0.055	0.100	0.040
h6	0.062	0.058	0.010	0.045	0.102	0.045
h7	0.066	0.042	0.003	0.027	0.106	0.045
h8	0.056	0.039	0.012	0.028	0.092	0.040
h9	0.039	0.037	0.015	0.028	0.068	0.029
h10	0.031	0.024	0.019	0.030	0.046	0.027
h11	0.025	0.009	0.015	0.024	0.033	0.022
h12	0.024	0.002	0.016	0.024	0.026	0.021
h13	0.025	0.001	0.016	0.025	0.022	0.022
h14	0.029	0.001	0.017	0.025	0.021	0.027
h15	0.033	0.001	0.024	0.030	0.023	0.036
h16	0.036	0.001	0.029	0.033	0.026	0.046
h17	0.039	0.008	0.036	0.038	0.037	0.053
h18	0.040	0.026	0.041	0.042	0.048	0.050
h19	0.042	0.046	0.041	0.048	0.064	0.041
h20	0.046	0.061	0.034	0.050	0.078	0.033
h21	0.057	0.062	0.019	0.053	0.093	0.033
h22	0.062	0.070	0.021	0.059	0.096	0.032
h23	0.060	0.070	0.022	0.061	0.096	0.033
h24	0.062	0.076	0.026	0.067	0.104	0.037

C Calculated Demand and Supply Slopes

Table IV

Slopes of Demand Curve for the 6 Typical Days

	TS Work	WI Work	SU Work	TS Wend	WI Wend	SU Wend
h1	-0.018	-0.012	-0.008	-0.011	-0.429	-0.011
h2	-0.025	-0.015	-0.007	-0.012	-0.422	-0.011
h3	-0.035	-0.016	-0.007	-0.012	-0.416	-0.011
h4	-0.049	-0.015	-0.006	-0.011	-0.407	-0.011
h5	-0.037	-0.014	-0.006	-0.009	-0.393	-0.011
h6	-0.023	-0.012	-0.006	-0.009	-0.404	-0.008
h7	-0.018	-0.016	-0.007	-0.008	-0.085	-0.006
h8	-0.013	-0.033	-0.011	-0.013	-0.017	-0.005
h9	-0.014	-0.085	-0.019	-0.023	-0.014	-0.005
h10	-0.012	-0.031	-0.018	-0.018	-0.014	-0.006
h11	-0.011	-0.018	-0.015	-0.013	-0.012	-0.007
h12	-0.011	-0.014	-0.016	-0.011	-0.012	-0.007
h13	-0.013	-0.014	-0.016	-0.012	-0.013	-0.008
h14	-0.013	-0.015	-0.018	-0.010	-0.011	-0.007
h15	-0.013	-0.015	-0.022	-0.010	-0.010	-0.008
h16	-0.013	-0.017	-0.021	-0.011	-0.008	-0.008
h17	-0.011	-0.018	-0.020	-0.011	-0.011	-0.008
h18	-0.011	-0.026	-0.016	-0.011	-0.018	-0.006
h19	-0.011	-0.029	-0.013	-0.013	-0.021	-0.006
h20	-0.011	-0.025	-0.011	-0.013	-0.019	-0.006
h21	-0.009	-0.012	-0.007	-0.010	-0.013	-0.006
h22	-0.010	-0.009	-0.007	-0.009	-0.013	-0.007
h23	-0.011	-0.009	-0.008	-0.009	-0.017	-0.009
h24	-0.011	-0.009	-0.008	-0.008	-0.023	-0.010

Table V

Slopes of Supply Curves for the 6 Typical Days

	TS Work	WI Work	SU Work	TS Wend	WI Wend	SU Wend
h1	0.010	0.007	0.033	0.008	0.005	0.018
h2	0.009	0.008	0.032	0.008	0.004	0.015
h3	0.009	0.008	0.028	0.008	0.004	0.013
h4	0.008	0.008	0.024	0.008	0.004	0.012
h5	0.008	0.008	0.026	0.008	0.004	0.012
h6	0.007	0.009	0.049	0.010	0.004	0.009
h7	0.008	0.014	0.186	0.015	0.003	0.009
h8	0.012	0.018	0.051	0.014	0.004	0.010
h9	0.017	0.020	0.042	0.015	0.006	0.013
h10	0.019	0.030	0.031	0.014	0.011	0.015
h11	0.022	0.077	0.035	0.016	0.015	0.017
h12	0.022	0.347	0.034	0.016	0.020	0.018
h13	0.019	0.658	0.031	0.015	0.021	0.017
h14	0.016	0.656	0.029	0.011	0.021	0.012
h15	0.014	0.656	0.021	0.009	0.018	0.008
h16	0.013	0.669	0.017	0.009	0.016	0.006
h17	0.013	0.085	0.014	0.008	0.012	0.006
h18	0.014	0.030	0.014	0.010	0.012	0.008
h19	0.015	0.017	0.015	0.011	0.010	0.012
h20	0.015	0.012	0.020	0.013	0.007	0.018
h21	0.011	0.011	0.035	0.011	0.006	0.019
h22	0.010	0.008	0.032	0.010	0.005	0.020
h23	0.010	0.008	0.032	0.010	0.005	0.022
h24	0.008	0.007	0.025	0.008	0.004	0.017

D Summary of Optimal Prosumer Decisions

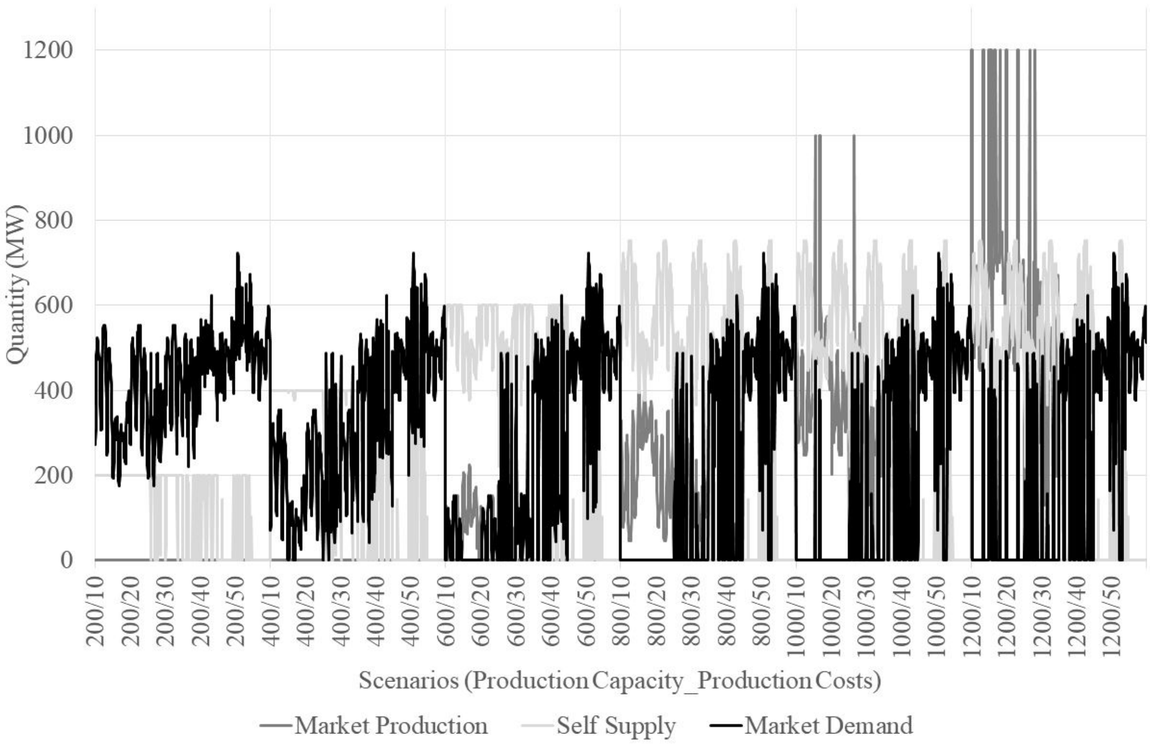


Figure 14: Optimal PS Decisions for 4,320 Typical Hours

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