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Local electricity market designs for peer-to-peer trading: The role of battery flexibility☆

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HIGHLIGHTS

- Analysis of end-user benefits in smart grids with peer-to-peer trade and battery storage.
- Proposal of two market designs in the presence of two storage location strategies.
- Implementation of a linear optimisation model for a community in London, UK.
- End-user potential savings of 31% due to peer-to-peer trade and private storage.
- Novel ideas for market design to integrate RES based on P2P trade and battery flexibility.

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ABSTRACT

Deployment of distributed generation technologies, especially solar photovoltaic, have turned regular consumers into active contributors to the local supply of electricity. This development along with the digitalisation of power distribution grids (smart grids) is setting the scene to a new paradigm: peer-to-peer electricity trading. The design of the features and rules on how to sell or buy electricity locally, however, is in its early stages for microgrids or small communities. Market design research focuses predominantly on established electricity markets and not so much on incentivising local trading. This is partially because concepts of local markets carry distinct features: the diversity and characteristics of distributed generation, the specific rules for local electricity prices, and the role of digitalisation tools to facilitate peer-to-peer trade (e.g. Blockchain). As different local or peer-to-peer energy trading schemes have emerged recently, this paper proposes two market designs centred on the role of electricity storage. That is, we focus on the following questions: What is the value of prosumer batteries in P2P trade?; What market features do battery system configurations need?; and What electricity market design will open the economical potential of end-user batteries? To address these questions, we implement an optimisation model to represent the peer-to-peer interactions in the presence of storage for a small community in London, United Kingdom. We investigate the contribution of batteries located at the customer level versus a central battery shared by the community. Results show that the combined features of trade and flexibility from storage produce savings of up to 31% for the end-users. More than half of the savings comes from cooperation and trading in the community, while the rest is due to battery's flexibility in balancing supply-demand operations.

1. Introduction

According to the European Union (EU) Strategy Energy Technology Plan [1], consumers (or energy end-users) are envisioned to be at the centre of the future energy system. A successful effort to actively involve consumers is the ongoing deployment and adoption of photovoltaic (PV) panels. Solar has proven to be a viable technology for the consumer, mainly due to policy incentives and its declining costs. Today, a similar narrative is starting to take place for electrical vehicles, batteries and other storage technologies. Batteries are a long-sought technology to increase the flexibility of supply-demand operations and are potentially a key technology in the EU energy transition [2]. Could batteries be the next technology deployed on a mass scale as is the case for solar PV? A current example of this development is the subsidy

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households in Germany receive when adding a battery system to their PV array [3].

As a consequence of the surge of distributed generation options (e.g. solar PV, batteries or small scale wind turbines), the rise of the prosumer[1] has brought new challenges to the established supply-demand dynamics in electricity generation and increased the need for on-site flexibility. For instance, in high-generation periods, the supply from renewable energy sources (RES) often exceeds a single prosumer's demand and their total generation therefore might not be fully exploited. The excess energy might be curtailed or fed back into the main grid. Curtailment, however, will reduce the profitability of the prosumer's generation capacity, which might lead them to invest in lower capacity. Feeding into the grid leads to other challenges such as the distributed generated electricity needing a fair price, and current highly subsidised feed-in tariffs might not be sustainable as the number of prosumers grows.

To address some of these challenges, peer-to-peer (P2P) trade has emerged as a new alternative to foster the deployment of distributed generation technologies. It allows a direct interaction between market participants without considering a third party involvement [4]. P2P is the ability to trade electricity with one another (consumer or prosumer), gain revenue for excess power, use a low-cost settlement system to reduce electricity bills and improve returns on investments in distributed generation. P2P trade opens the possibility to switch energy suppliers on a minute-by-minute basis and buying-selling (prosumers) electricity based on one's own preferences. For instance, a P2P system might incorporate blockchain technologies to keep track of the electricity amount traded and have a transparent automated settlement system.

However, P2P energy trade concepts in microgrids are still at an early stage in the literature as there is no consensus on what business model or market design will help to develop local electricity markets. In this regard, the digitalisation of distributed grids will enable P2P trade and facilitate the establishment of local bidding pools that can eventually be linked to existing electricity markets (day-ahead or intraday electricity markets). This will lead to various market design questions, such as: Which local electricity market designs and P2P mechanisms will provide the *right* framework for an efficient exploitation of the digitalisation of power distribution grids? How will the broader electric power market evolve if additional technological features such as local intermittent RES and battery flexibility are introduced? In this paper, we assume that digitalisation technologies and smart grids are installed and have the capability to carry out P2P trade. We focus on the role of battery storage under different distributed energy system configurations and define market governing rules. In other words, we study the battery storage potentials for end-users in the presence of P2P trade guided by the following research questions:

- What is the value of batteries in P2P trade? What new market features do they bring?
- What electricity market design will open the economic potential of end-user batteries?

To address these questions, we develop a P2P trading model (linear programming based) in order to evaluate the end-user benefits of two distinct market designs and distributed generation system configurations centred on the flexibility of battery storage: decentralised versus centralised storage (see Fig. 1). Specifically, the value of battery storage and associated market design features in combination with P2P trade are examined. Our model minimises the electricity costs of a small community subject to a local supply-demand balance which schedules the operation of RES, grid consumption, battery usage and P2P trade.

The community comprises a set of houses of consumers and prosumers which are heterogeneous both in demand patterns and technology portfolios. The houses are equipped with either a wind turbine, a PV panel, both or none of these technologies. Additionally, the houses have the possibility of storing energy in either a decentralised privately owned battery or a commonly accessible centralised battery. We use historical demand, generation and price data for a community of houses in London, United Kingdom (UK). To understand the value of local P2P trade and battery flexibility, we compare the outcomes of the two proposed market designs to a reference case that does not incorporate either of the two features. We find that the interplay of storage and P2P trade can save up to 31% percent of the electricity costs for a community. Renewables cover around half of the demand of the community when supported by P2P trade and batteries. From this results, we observe a significant increase in self-sufficiency, utilisation of RES and compelling cost savings.

The remainder of the paper is structured as follows: Section 2 reviews related literature and positions in recent research on local market designs. Section 3 describes the proposition of two distinct market designs for the combination of P2P trading and battery storage, this section also details the modelling approach. The case study data sources and modelling results are presented in Section 4. Section 5 concludes and indicates further research directions.

2. Related literature

Although not widely incorporated in today's electricity markets, the direct interaction (energy trading) within a group of P2P prosumers has recently been explored or partially implemented in pilot projects, e.g. Brooklyn Microgrid [5], Enerchain [6], and others.[2] Zhang et al. [7] review these projects. A similar review by Park and Yong [8] details a specific comparison of the applied business models for the different projects in place. These reviews note that the P2P energy trading concept is at a relatively early stage. No consensus exists on what market-regulatory mechanisms and business models should be in place to facilitate P2P trading. Zhou et al. [9] assess the economic performance of three different P2P sharing models and find that a market based on dynamic price rates is worthwhile. Similar results are found by Long et al. [10] who additionally investigated an auction-based P2P method. In further work, Zhou et al. [11] propose a multiagent-based simulation framework to evaluate P2P energy sharing mechanisms. In other related work, a P2P bidding system has been proposed by Zhang et al. [12] for a grid-connected microgrid, and analysed using non-cooperative game theory. The authors conclude that P2P trading bears large potentials for a better integration of distributed energy resources (DER) into the power system, while ensuring the balance between local generation and demand. The feasibility of P2P energy trading in low-voltage electricity networks was investigated by Long et al. [13]. Their paper entails guidelines for constructing future distribution networks for facilitating a P2P trading market paradigm. The impact of novel energy sharing systems on socio-economic structures is analysed in a theoretical framework by Giotitsas et al. [14].

P2P interaction in a residential community needs proper pricing schemes. Fridgen et al. [15] note that 'one rate does not fit all'. They identify twelve tariff structures for residential microgrids, and simulate the response of 100 microgrids to the designed tariffs. Their findings showcase that tariff designs should consist of capacity and customer charges, while averting mere volumetric billing based on electricity use. Tariffs that account for system and energy retail costs would decrease customers' electricity bills while supporting peak-shaving

[1] Prosumers are consumers that produce electricity from privately owned generation technologies.

[2] Pilot projects include among others: Vandrebron, Netherlands (https://vandebron.nl/), The Sun Exchange, South Africa (https://thesunexchange.com/), Elblox, Germany (https://www.elblox.org/), Power Ledger, Australia (https://powerledger.io/), and Piclo, UK (https://piclo.uk/).

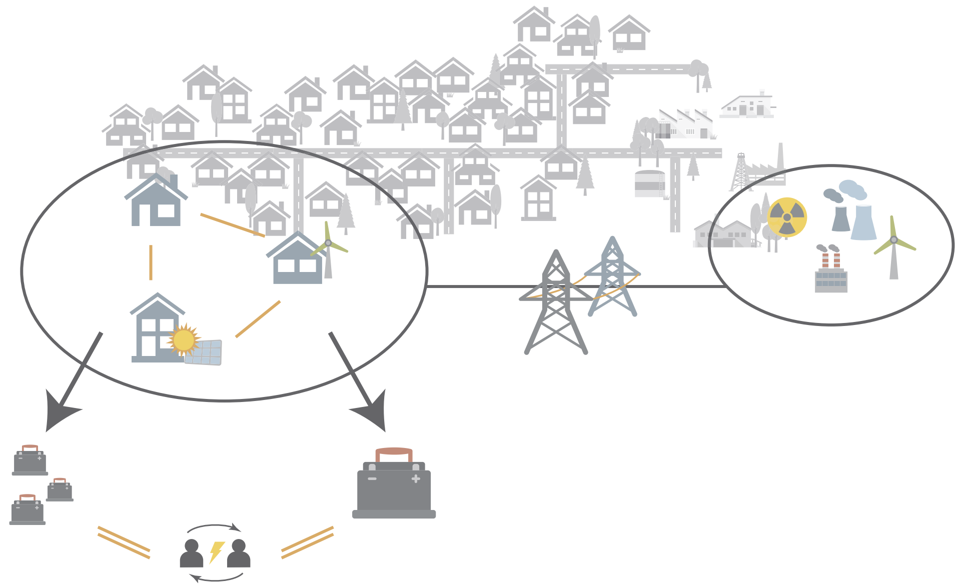


Fig. 1. Peer-to-peer trade considering the role of centralised or decentralised batteries.

opportunities. Abdelmotteleb et al. [16] propose an efficient distribution network charge that promotes efficient consideration of network usage and investment. In a case study in Australia, Passey et al. [17] investigate the cost-reflectivity of demand charge network tariffs. They demonstrate how to adjust the structure of demand charge tariffs to align the electricity bills of the customers to their share of the peak demand. For P2P trade, Zhang et al. [18] present a trading platform (Elecbay) in a microgrid. They build a system architecture to which they apply a game theoretical bidding system.

One of the challenges in P2P trading is the need to have information close to real-time of locally produced electricity as well as to track trading decisions for an accurate calculation of electricity bills between prosumers. Murkin et al. [19] discuss requirements and key benefits of P2P trading markets. Special features in these markets are the ability to switch energy suppliers on a minute-by-minute basis and buying electricity based on own preferences. Blockchain is found to offer a platform to incorporate those features in a local P2P market. The authors present an application of blockchain technologies for enabling P2P trading. The determination of a design for P2P trade based on distributed ledgers to enhance efficient and resilient transactions within an energy community as well as acceptance by the wholesale market has been examined by Ernst et al. [20]. Long et al. [21] propose a two-stage control method to realise P2P trade in a community energy system with an energy sharing coordinator. The authors find that P2P trading is more valuable than peer-to-grid selling with an electricity bill reduction of 30% for the community.

P2P market design has some modelling features similar to the idea of creating local electricity markets through aggregators, e.g. Bremdal et al. [22] and Olivella-Rosell et al. [23]. Parag and Sovacool [24] identify three prosumer market models comprising P2P, prosumer grid integration and organised groups of prosumers. Market design approaches on flexibility contracting including the possibility of flexibility exchange in a local market has been discussed in Ramos et al. [25]. Ottesen et al. [26] consider the perspective of an aggregator providing flexibility services to the broader grid. Motalleb and Ghorbani [27] propose a game theoretic market model to obtain optimal bidding strategies for aggregators selling energy from storage devices. Flexibility market designs for aggregators within a distribution network has been provided by Olivella-Rosell et al. [28]. Mathieu et al. [29] present the open-source agent-based testbed DSIMA to simulate interaction models for the exchange of flexibility services at distribution network level. However, the role of storage and the associated P2P local market design around a storage entity has not been extensively examined by any of these references. From the projects in place, only the Sonnen-Community project in Germany[3] includes battery storage as centrepiece in its design.

The recent progress in the digitalisation of the distribution grid towards smart grids has opened the discussion of formulating local electricity markets. Smart grid is a broadly defined term used in various topics and applications, often describing some sort of digitalised control system or technology [30,31]. A more specified overview on smart grids in the British power sector is given by Jenkins et al. [32], with an in-depth description of current policy and technical drivers, as well as incentive mechanisms, and the recent progress of the power industry. Kakran and Chanana [33] provide an up-to-date overview on recent progress and future key advantages in demand side management and demand response mechanisms combined with distributed generation (DG). The combination of smart grid and energy storages and resultant policy recommendations have been discussed by Amoretti [34], Crespo del Granado et al. [35] and Zame et al. [36]. The authors emphasise the need for a re-conceptualisation of the traditional power grid model as this might become outdated if smart grid and distributed generation technologies become widespread.

Current literature, however, does not specifically focus on the market designs of P2P cooperation for the end-users in microgrids. Although the general idea has been mentioned by Barbato et al. [37], the possible cooperative interaction between heterogeneous prosumers and consumers has not yet been comprehensively described in the literature. Moreover, the synergy of P2P trading and placement of battery storage has not been deeply investigated. For example, Fortenbacher et al. [38] favour the placement of decentralised batteries at the end-user level, but do not consider P2P trading. In short, the question on efficient market designs around P2P trading and battery storage systems remains, to our knowledge, not fully explored in previous research.

3. Modelling local electricity markets and prosumers

To efficiently use DG and stimulate P2P trading, we propose two distinct local based electricity market designs for communities of

[3] Further information available at https://sonnenbatterie.de/de-at/sonnencommunity.

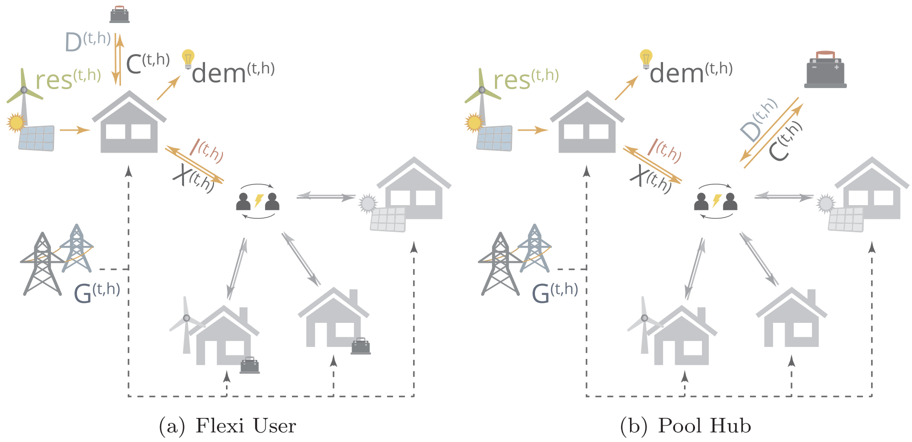


Fig. 2. Local electricity market designs in different setups: decentralised (a) versus centralised battery (b).

prosumers and consumers. The objective is to investigate the role of battery storage and how it is affected by market design rules. We set up two systems varying in the installation level of battery storage, and subsequently define rules for prices, P2P trade and battery usage.

To this end, consider a community of H prosumers and consumers that are connected through a local electricity distribution network. Each prosumer has energy generation technologies, i.e. wind and/or solar PV. The objective of this community is to minimise costs of electricity consumption from the transmission grid by prioritising self-sufficiency. This is possible by incentivising direct P2P trade within the community or employing batteries for balancing. Fig. 2 schematically shows a community of four houses in which a battery storage is located either decentralised at the house level (a) or centralised within the community (b). See Table 1 for the declaration of variables used.

3.1. Market design for peer-to-peer trading

A market design entails the defining of rules for the functioning of a market and steers its actions [39]. It determines and defines the rules aiming to ensure an efficient and fair market functioning. Hence, to investigate the value of storage and P2P trade in a local market, we define and compare rules on trading, and on how the storage can be managed given different sets of rules to provide most benefit to the community. We call these two distinct market designs *Flexi User* and *Pool Hub*.

Table 1
Designated sets, parameters and variables of the mathematical model.

Sets	
$t \in T$	Hours t in time horizon T
$h, p \in H$	Houses h and peers p in community H
Scalars	
ψ^{P2P}	Distribution network losses and conversion of DG for P2P sale
$\bar{s}/\underline{s}$	Upper/lower bounds of storage level in battery
α/β	Maximum charge/discharge rate of battery
η^c/η^d	Battery charging/discharging efficiency
Parameters	
$dem^{(t,h)}$	Demand of house h in time step t
$res^{(t,h)}$	Renewable energy production of house h in time step t
$p_G^{(t)}$	Price of electricity from the grid in time step t
$p_{p2p}^{(t,h)}$	Price of electricity in the local market for house h in time step t
$p_C^{(t)}$	Price of charging the common battery in time step t
$p_D^{(t,h)}$	Price of discharging the common battery in time step t
Variables	
$C^{(t,h)}$	Charge of battery of house h in time step t
$D^{(t,h)}$	Discharge of battery of house h in time step t
$G^{(t,h)}$	Grid consumption of house h in time step t
$I^{(t,h)}$	P2P electricity purchase of house h in time step t
$I_p^{(t,h\leftarrow p)}$	P2P electricity purchase of house h from peer p in time step t
$S^{(t,h)}$	Energy storage level in battery of house h in time step t
$X^{(t,h)}$	P2P electricity sale of house h in time step t
$X_p^{(t,h\rightarrow p)}$	P2P electricity sale of house h to peer p in time step t

Fig. 2 shows the setups underlying the two distinct market designs. The *Flexi User* is designed for a setting with individual batteries at consumer level. Then, the structure in the *Pool Hub* considers a large battery at the community level. For both designs, we allow the trade of locally generated electricity within the community, where trade is the ability to sell excess electricity from renewable energy sources to peers. Each of the two setups gives the storage entity a certain role leading to the following distinct market design definitions:

- **Decentralised storage – *Flexi User* Market:** This market design applies rules to the system setup with individually owned batteries. Prosumers and consumers within a community can trade locally produced energy at a dynamic local P2P price. Privately owned storage can be charged by DG from prosumers within the community.
- **Centralised storage – *Pool Hub* Market:** This market design applies rules to the system setup with one commonly owned battery. Prosumers and consumers can trade locally at the same dynamic local P2P price as in the *Flexi User* case. Contrary to the *Flexi User*, only one big storage entity exists which is located centrally and owned by the community. Charging of the battery can only originate from the renewable generation of prosumers within the community, and will be compensated. Discharge is available for everyone – prosumers and consumers – at a slightly higher rate than the charging compensation rate.

To create a fair marketplace, these two designs entail certain rules for prices. Table 2 lists main assumptions on specific prices as well as summarises the features of the two designs. To incentivise local trade, we introduce a price mechanism for the P2P trade that ensures a lower price for electricity on the local level.

Aside from the main rules on price determination and storage accessibility, we only allow the battery to charge from DG and assume that prosumers cannot feed to the grid. On the one hand, we lower the arbitrage potential that can be achieved when shifting grid consumption by using the battery. On the other hand, we force curtailment to some extent. These rules are discussed and explored in our results and we are aware that this might limit the prosumers' profit in countries with high subsidies for feed-in. Moreover, any kind of active trading with the grid would require a new interface between the community

Table 2
Overview on proposed local market designs and system setups.

	Flexi User	Pool Hub
System setup:	Decentralised	Centralised
Prosumer battery:	Availability: Fixed max. capacity (private)	Availability: Flexible capacity (community owned)
Electricity sources:	Grid, P2P trade	Grid, P2P trade, storage
Resource charging battery:	DER, P2P trade	DER, P2P trade
	Grid price (p_G)	Grid price (p_G)
	P2P trade price (p_{p2p})	P2P trade price (p_{p2p})
Prices:	$p_{p2p} < p_G$	Discharge price (p_D)
		Charge compensation (p_C)
		$p_C < p_{p2p} < p_D < p_G$

and the network operator which is not explored in this paper.

In addition to the rules on storage, trade and prices defined in the market design, we need to make some assumptions with respect to model complexity and computational effort. We assume unlimited supply from the grid at any time. From the physical perspective, we neglect battery degradation and characteristics of electricity distribution, i.e. load flow. Investment costs of DG are not accounted for in any prices. Although we are aware of uncertainty in generation from RES, we do not consider any uncertainty in production or prices.

3.2. Model formulation

To model the features of local trading, we focus on the interaction of four main operational supply-demand decisions: (1) consumers/prosumers demand electricity from the main grid, (2) prosumers use their own distributed generation, (3) P2P trading within the community, and (4) battery storage balancing. Hence, a community of prosumers and consumers faces trading decisions mainly based on RES surplus, battery flexibility, grid and trade prices. A multi-period linear programming model optimises these decisions in half-hourly time intervals (t) over a time horizon T. The objective function comprises electricity costs for the whole community and is subject to supply, battery and trade constraints. Table 1 summarises the nomenclature used for the model's mathematical expressions. For a better overview, exogenously predetermined parameters and scalars are denoted in lower case, whereas variables are represented by upper case letters.

We consider the houses ($h \in H$) to have diversity on demand and generation profiles. Each house requires a balance of supply and demand. That is, supply from renewable generation $res^{(t,h)}$, grid consumption $G^{(t,h)}$, battery discharge $D^{(t,h)}$ and direct P2P purchase $I^{(t,h)}$ should match the sum of demand $dem^{(t,h)}$, battery charge $C^{(t,h)}$ and P2P sales $X^{(t,h)}$ for each house $h \in H$ in each time step $t \in T$. In short, we have the supply greater equal to demand by Eq. (1)[4]:

$$\overbrace{res^{(t,h)} + G^{(t,h)} + D^{(t,h)} + I^{(t,h)}}^{\text{RES+Grid + Battery discharge + P2P purchase}} \geqslant \overbrace{dem^{(t,h)} + C^{(t,h)} + X^{(t,h)}}^{\text{Demand+Battery charge + P2P sale}} \tag{1}$$

3.2.1. Peer-to-peer trade

The community is interconnected to allow prosumers a direct trade of electricity with their fellow peers. Enabled trade needs to follow certain rules. The overall sales quantity $X^{(t,h)}$ for each house $h \in H$ is defined as the sum of all electricity flows $X_p^{(t,h\to p)}$ from this house $h \in H$ to its peers $p \in H$, Eq. (2).

[4] All equations hold true for all $h \in H,\ t \in T$.

$$X^{(t,h)} = \sum_{p \neq h} X_p^{(t,h\to p)} \tag{2}$$

Given that

$$I_p^{(t,h\leftarrow p)} = \psi^{P2P} \cdot X_p^{(t,p\to h)} \quad \forall\ p\ \neq\ h, \tag{3}$$

the change of the flow direction indicates a purchase $I_p^{(t,h\leftarrow p)}$ of one house $h \in H$ from its peer $p \in H$. The overall purchased quantity per house, $I^{(t,h)}$, is then specified by Eq. (4).

$$I^{(t,h)} = \sum_{p \neq h} I_p^{(t,h\leftarrow p)} \tag{4}$$

As no grid feed-in is considered, the sold and purchased quantity can, thus, only stay within the community. The sum of sales over all houses needs to equal the purchases as follows with Eq. (5).

$$\sum_h \psi^{P2P} \cdot X^{(t,h)} = \sum_h I^{(t,h)} \quad \forall\ t \in T. \tag{5}$$

3.2.2. Market specific constraints: battery decisions and objective functions

The two market designs consider different rules for the availability, capacity and pricing of storage within the community. Thus, the models for each design optimise slightly different objectives subject to varied constraints for the storage entity. For all considered models, the overall objective of cost minimisation is subject to the supply-demand, P2P trade and the varying storage constraints.

Flexi User

In the *Flexi User* market with decentralised storage, costs arise when a prosumer consumes from the grid or buys from a fellow peer. However, in the P2P trade, the selling peer earns money and thereby reduces the costs of electricity for the overall community. As the amount someone pays and the other one earns will cancel out, we leave these terms out of the optimisation. Thus, the objective function for this case minimises the sum of costs for grid consumption $G^{(t,h)}$, Eq. (6).

$$\min \sum_h \overbrace{\sum_t [p_G^{(t)} \cdot G^{(t,h)}]}^{\text{Grid consumption}} \tag{6}$$

This cost minimisation is subject to the supply-demand balance, Eq. (1), the trade constraints, Eqs. (2)–(5), and restrictions for the private battery. For the visualisation of all components, Fig. 2(a) summarises the flows.

The private batteries underlie certain physical characteristics. A lower bound $\underline{s}$ and an upper bound $\bar{s}$ limit the storage level $S^{(t,h)}$ per battery according to Eq. (7).

$$\underline{s} \leqslant S^{(t,h)} \leqslant \bar{s} \tag{7}$$

The battery's charging and discharging is limited to a specified rate of α and β, respectively. The rates are mathematically represented in Eqs. (8) and (9).

$$0 \leqslant C^{(t,h)} \leqslant \alpha \tag{8}$$

$$0 \leqslant D^{(t,h)} \leqslant \beta \tag{9}$$

The overall storage level for the battery in a time step t is determined by Eq. (10) with the charge $C^{(t,h)}$ and discharge $D^{(t,h)}$ in this period being subject to the efficiency coefficients η^c and η^d.

$$S^{(t,h)} = S^{(t-1,h)} + \eta^c \cdot C^{(t,h)} - (1/\eta^d) \cdot D^{(t,h)} \tag{10}$$

Pool Hub

In the *Pool Hub* case with a centralised storage, costs arise for three components: grid consumption, P2P trade and discharging the centralised battery. Furthermore, we compensate prosumers for charging and considers their incomes from P2P trade, see Fig. 2(b). The objective function of the *Pool Hub*, Eq. (11), needs hence two more components that add costs for battery discharging $D^{(t,h)}$ and compensations for charging $C^{(t,h)}$.

$$\min \sum_h \left(\overbrace{\sum_t [p_G^{(t)} \cdot G^{(t,h)}]}^{\text{Grid consumption}} + \overbrace{\sum_t [p_D^{(t)} \cdot D^{(t,h)}]}^{\text{Battery discharge}} - \overbrace{\sum_t [p_C^{(t)} \cdot C^{(t,h)}]}^{\text{Battery charge}} \right) \tag{11}$$

The big battery is limited to the physical constraints formulated in Eqs. (7)–(9) with the constants $\underline{s}$, $\overline{s}$, α, β, η^c and η^d being different for the greater centralised storage entity. The overall storage level will no longer be depending on a single house's charge or discharge, but takes into account the sum of all flows from and to all houses to the battery. Eq. (12) comprises the sums of discharge $D^{(t,h)}$ and charge $C^{(t,h)}$ for the centralised battery and adds these up to the overall storage level $S^{(t)}$.

$$S^{(t)} = S^{(t-1)} + \eta^c \cdot \sum_h C^{(t,h)} - (1/\eta^d) \cdot \sum_h D^{(t,h)}, \ \forall \ t \in T. \tag{12}$$

4. Results and analysis

The numerical analysis examines firstly the battery's role of flexibility for the consumer and for P2P trade. The results demonstrate how energy storages smooth peak demands to the grid by a better utilisation of the distributed energy. Secondly, the analysis discusses the impact of the proposed market designs and system configurations on the value of storage and P2P trading.

4.1. Model implementation and data

The data comprises the characteristics of distributed generation technologies (RES and battery systems), demand profiles, the electricity price of grid consumption and the P2P trade prices. Data sets cover the year 2012 in a time resolution of 30 min. The local trade assumes losses of 7.6% through the local network (see [40]). The models are run for the first nine months of the year 2012, due to the constrained accessibility of matching demand and spot price data sets. We apply the model and show the results for three different sets of community houses in our analysis. The models are implemented in GAMS.[5] The linear program optimisation comprises 1,359,605 variables and 1,029,602 constraints and is solved in less than one minute on a regular computer.

4.1.1. Distributed generation

Wind Power: Wind power generation mainly depends on two predominant performance factors: the wind speed (i.e., exogenous weather condition) and the height of installation. For our actual houses in the UK, we consider a small wind turbine of 2.3 kW which follows common designs for the off-grid market.[6] The wind power time series for this small wind turbine was calculated by fitting a polynomial curve to the wind speeds and the output power curve. A similar process on converting wind speeds to power is detailed in Crespo del Granado et al. [35,41].[7] The wind speed data was taken from the UK Meteorological Office from a climatological station near London.

Solar PV: The PV power in a half-hourly resolution was obtained by a conversion of global horizontal irradiation and temperature data for a pre-specified PV installation. The PV system has a total rated power of 4 kW with an efficiency of 21.4% on an area of 20.8 m^2. For the UK, PV panels are recommended to be tilted at an angle of 35 degrees in relation to the incoming solar irradiation, thereby maximising the power output. The global horizontal irradiation and temperature data was retrieved from the HelioClim-3 archives,[8] together with meteorological data from MERRA-2[9] for the Greater London area. Note that this solar dataset covers the year of 2006 as we were not able to obtain a higher resolution data (in 30 min intervals) for 2012.

4.1.2. Battery storage

We consider two types of battery storage devices. For the decentralised battery cases, we choose a 4 kWh sonnenBatterie with a one-way efficiency of up to 98% [43]. The charge and discharge rates are dependent on the performance of an inverter with a nominal power of 2.5 kW and a maximal efficiency of 96%. Taken together, this results in a full charging/discharging time of about 100 min with an overall round-trip efficiency of 88.5%. For the centralised storage, we consider the Tesla Powerwall 2AC with a capacity of 13.2 kWh and a round-trip efficiency of 89% [44]. The charging and discharging are constrained by an inverter of 3.3 kW nominal power, resulting in a full charging/discharging within 4 h (8 model time steps). We assume no degradation processes and do not consider lifetime expansion by smart charging control devices.

4.1.3. Demand profiles

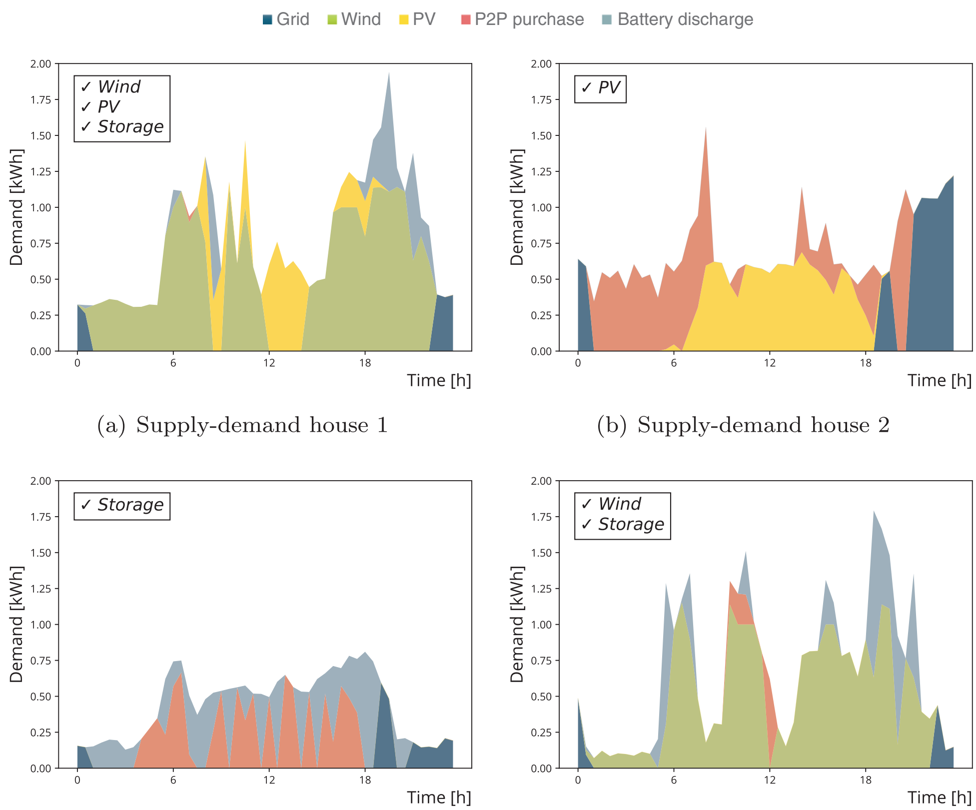
Demand datasets for the houses are taken from the database of the Low Carbon London project[10] which collected the energy consumption of 5567 households in the Greater London Area, UK. We choose demand patterns from the group that was subject to a static pricing scheme with a flat rate tariff of 14.2 pence/kWh. The consumers are differentiated concerning their prosperity by a classification of residential neighbourhoods in the UK: affluent, comfortable and adverse. With higher electrical consumption in general and the actual financial possibility of installing DG on their property, the taken samples for the houses belong to the affluent group. The chosen houses have differences in their consumption pattern, both in quantity and temporal allocation throughout the day. Specifically, we consider three sets of communities that each comprise four different houses. One exemplary community has the following demand characteristics and assumed on-site generation technologies per house:

- **House 1** has an average monthly demand of 1590 kWh/month, a 2.3 kW small wind turbine and a 4 kW roof-top PV installation. It also includes a residential battery storage of 4 kWh.
- **House 2** is only equipped with a solar PV installation of 4 kW and has an average monthly demand of 690 kWh/month.
- **House 3** owns a battery storage of 4 kWh but no distributed generation. The average monthly demand sums up to 660 kWh/month.
- **House 4** has an average monthly demand of 900 kWh/month. It includes the 2.3 kW wind turbine and a residential battery of 4 kWh.

4.1.4. Electricity prices

The optimisation and comparison of the proposed market designs highly depend on the prices assumed to the different sources of electricity consumption (see Table 2). We use an exogenously given dynamic price for the grid and determine all other prices based on this dynamic time series. The time series of the reference price data (RPD) for the UK electricity spot market is retrieved from the former APX Group.[11] The RPD accounts for about one thirds of the electricity bill the end-users pay in the UK. Consequently, the RPD time series was

[5] GAMS software, for further information refer to https://www.gams.com/.
[6] See e.g. model Skystream 3.7, http://www.windenergy.com/products/skystream.
[7] We are aware that there exist other more accurate methods to obtain wind power time series. See e.g. Shokrzadeh et al. [42] for an in-depth discussion of more advanced methods.
[8] For further information, please refer to http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free.
[9] For further information, please refer to https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/.
[10] For further information, please refer to https://data.london.gov.uk/dataset/smartmeter-energy-use-data-in-london-households.
[11] For further information, please refer to http://www.apxgroup.com/market-results/apx-power-uk/ukpx-rpd-historical-data/.



(a) Supply-demand house 1 (b) Supply-demand house 2

(c) Supply-demand house 3 (d) Supply-demand house 4

Fig. 3. Demand cover for exemplary houses on a day in spring in the *Flexi User* market.

scaled up to represent typical price levels customers have to pay at the residential level. The average of the adjusted RPD time series was set to the flat rate of 14.2 pence/kWh that the customers in the static pricing scheme of the Low Carbon London project had to pay.

A reasonable price for P2P trade should reflect the willingness of each prosumer to pay for an extra unit of electricity under the assumption that there is no possibility for local trade or storage. The shadow price of each single prosumer can be seen as the willingness to pay of each prosumer. This approach is analogous to the proposition of Abbaspourtorbati et al. [45] who calculated clearing prices by the dual variables of the energy balance equations. To calculate the P2P prices, we independently minimise each prosumer's costs for electricity subject to the supply-demand balance in Eq. (1) in the absence of storage and interconnection. The result of the separate optimisations provides a dynamic willingness to pay for electricity of each house in each time step. Since this P2P price should not consider the fees for network and grid usage (typically one third of the consumer bill, see [46]), we downscaled these prices by 36% as we assume that grid usage costs do not occur when electricity is traded locally in the community. Reflecting the willingness to pay for electricity, we implement these downscaled shadow prices as the house's purchase price for P2P trade.

For the *Pool Hub* market, we need two more dynamic price schemes. As the charging of the central battery should be compensated, prosumers receive the wholesale spot price for electricity when they charge the battery. The discharging is priced according to each house's willingness to pay (i.e. the P2P price $p_{P2P}^{(t,h)}$) plus an additional fee to avoid arbitrage operation through the battery. This additional fee is set equal to the charging compensation $p_C^{(t)}$ at this time. Thus, the price for discharging is equal to the sum of the P2P trade price $p_{P2P}^{(t,h)}$ and the charging compensation $p_C^{(t)}$ and differs among the houses.

4.2. *Flexi User* market results

The *Flexi User* case incorporates local trade and battery at house level. The decentralised storage, thus, allows for storing of one's own generation at no costs. Through trade, prosumers can sell their generation surplus and stored energy in the local market.

Running our model based on the rules of a *Flexi User*, we minimise the total costs of grid electricity consumption in the community. Each prosumer tries to cover demand by their own DG and then by buying the next cheapest energy source on the market (peers). This leads to differing sources of electricity consumption per house. Fig. 3 illustrates the model's supply-demand decisions on how each of the exemplary depicted houses (customers) covers consumption on a single day in spring (19th April, 2012). We observe the following:

- Interaction and storage reduce grid consumption.
- Peer-to peer trade allows the community to cover all demand by renewable energy sources during large parts of the day.
- Storage covers great shares of demand especially during peak time.

This exemplary spring day shows how P2P trade and energy storage are used by the community to cover their demand. A pure consumer (house 3) covers demand mainly by P2P purchases due to exploiting cheaper local P2P prices. All prosumers are able to use their own generation and store excess electricity for later use. Drawing electricity from the grid is only necessary during evening peak when local electricity generation, especially PV supply, is comparatively low or nonexistent. At night when prices are low, prosumers also cover demand by

Table 3
Average results for the three communities: the reference case (no P2P trade, no storage) along with the different system configurations.

	Battery location and case		
	No storage	Decentralised	Centralised
No P2P Trade			
	Reference		
Total costs	£3049	£2713	£2585
Grid consumption [kWh]	20,345	18,567	15,478
% DG curtailed	56.9%	50.4%	10.1%
% demand by			
Battery		9.7%	15.6%
DG	35.2%	31.1%	35.2%
Grid	64.8%	59.2%	49.2%
Storage savings		*£336 (−11%)*	*£464 (−15%)*
P2P Cooperation			
		Flexi User	**Pool Hub**
Total costs	£2557	£2118	£2321
Grid consumption [kWh]	16,980	14,941	15,007
% DG curtailed	52.8%	12.1%	10.6%
% demand by			
Battery		12.4%	6.5%
P2P	13.4%	10.1%	13.1%
DG	32.6%	30.0%	32.7%
Grid	54.0%	47.5%	47.7%
Storage savings		*£439 (−17%)*	*£236 (−9%)*
Trade savings	*£492 (−16%)*	*£594 (−22%)*	*£264 (−10%)*
SAVINGS total	***£492 (−16%)***	***£931 (−31%)***	***£728 (−24%)***

consuming from the grid and use their production to charge the battery. As the chosen day presents a good supply from wind, house 1 and 4 satisfy major parts of demand in the community. Generation from DG will differ among the seasons and thereby highly influence the usage of storage as charging is assumed to be only possible from local DG.

To estimate the value of interaction and storage, we take a step back and run separate tests concerning these two features. Today's market, a market without interaction and storage, acts as the reference case. In Table 3, we summarise the main average outcome of all tests and present the average values of trade and storage based on the three community setups. The reference case is presented with the characteristics of no P2P cooperation and no storage. Adding the features of cooperation and storage independently and step by step until we get to the *Flexi User* design, we yield the following main insights:

- The pure implementation of P2P trade leads to savings of £445.
- In the presence of trade, decentralised storage combined in a *Flexi User* market generates additional savings of £427.
- Grid consumption reduces from a share of 64% in the reference market to 49% in a *Flexi User* market.
- Half of the demand can be covered from distributed generation within the community.

4.3. Pool Hub market results

The *Pool Hub* market design considers an interconnected community of consumers with a central storage device. P2P trade is priced at the same dynamic rate as in the *Flexi User* case. As the storage is no longer owned privately, discharging from the central battery will be priced and charging compensated. Charging the battery from the grid is not allowed.

Applying these rules, we obtain slightly different patterns for the consumption of each house. Fig. 4 shows the source of consumption for the exemplary depicted houses on the same day in spring. We gain the following insights:

- Interaction and storage cover a significant share of the demand in the *Pool Hub* market.
- Prosumers tend to discharge the battery at different times.
- Grid consumption in peak time is lowered significantly and shifted to night or early morning times.

All houses use the battery or DG during the evening peak to avoid high prices from the grid. As the chosen day provides a lot of electricity from wind, house 1 and 4 can sell and charge the battery at high compensations in the morning and evening, and discharge at low rates during the day. The consumer (house 3) covers its demand to a great extent from P2P purchases and consumes from the grid at high demand and low generation times. Only in periods of high demand is it necessary to draw from the grid at the highest rate.

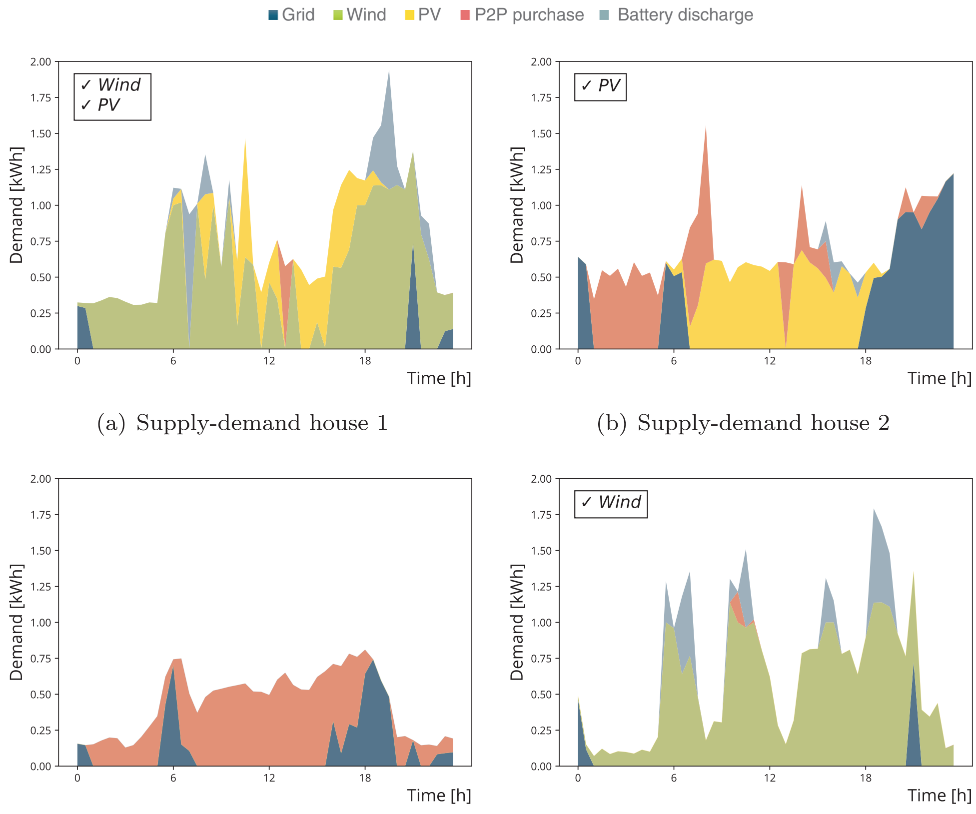
As seen in Table 3, the additional analysis of taking away P2P connection in the presence of a centralised storage results in savings compared to the reference case. Implementing a common storage only saves up to £418. Introducing direct trade to a community with a central battery leading to the Pool Hub market saves additional £243.

4.4. Comparison: sensitivity of prices and system configuration

The two proposed market designs – *Flexi User* and *Pool Hub* – incorporate market rules on prices, P2P trade and battery usage. The difference in rules stems from the difference in ownership of the implemented battery storage. The application of these rules incentivises thereby the use of different market features (battery storage or direct P2P trade) within their setups. Hence, the supply-demand decisions of the community differ among the cases analysed. Fig. 5 shows the average source of supply for the exemplary depicted community over one day, taking into account the overall time horizon of nine months. Applying the *Flexi User* market rules, the community consumes, on average, to a large extent directly from the renewable sources during the day, and uses the storage in the evening to reduce grid consumption (see Fig. 5, left). The rules of a *Pool Hub* market design lead to slightly other supply-demand decisions (see Fig. 5, right). The community constantly discharges a small amount of electricity from the centralised battery during the day and only a slightly bigger share in the evening. This, in turn, leads to a greater need for grid consumption in the evening. The direct consumption from renewable generation is greater during the day as P2P trade is also very frequently employed (see also Table 3 for the average percentages of the three community setups).

The introduction of either market design leads, however, to significant savings compared to the reference case (no P2P cooperation and no battery). Table 3 shows that savings for the *Flexi User* are slightly higher than for the *Pool Hub*. To identify the main drivers of the results, we take a closer look at the two main influencing factors: system configuration and market design. The former comprises differences in physical battery characteristics and the demand patterns of the houses. The latter includes strong rules on pricing. In Table 4, we give an overview on the influencing factors.

The battery characteristics vary slightly among the presented system configurations. The aggregated capacity for decentralised storage at 12 kWh is slightly smaller than for the centralised storage. However, the charge and discharge rates for each residential battery are at almost the same rates as for the central battery, due to the characteristics of the installed converter. This allows for a greater overall charging and discharging per period for private storage. However, the round-trip efficiency of the smaller batteries is assumed to be slightly lower resulting in higher losses during the storing process. To validate this hypothesis, we ran a test on varying the battery characteristics of the *Pool Hub* design to match the aggregated properties of the *Flexi User* market. We observe only a slight increase of 0.3% in the total costs for the Pool Hub market. Thus, the different storage characteristics do not have a significant influence on the decisions of the model. Moreover, we looked further into different setups of the community, i.e. we



(a) Supply-demand house 1 (b) Supply-demand house 2

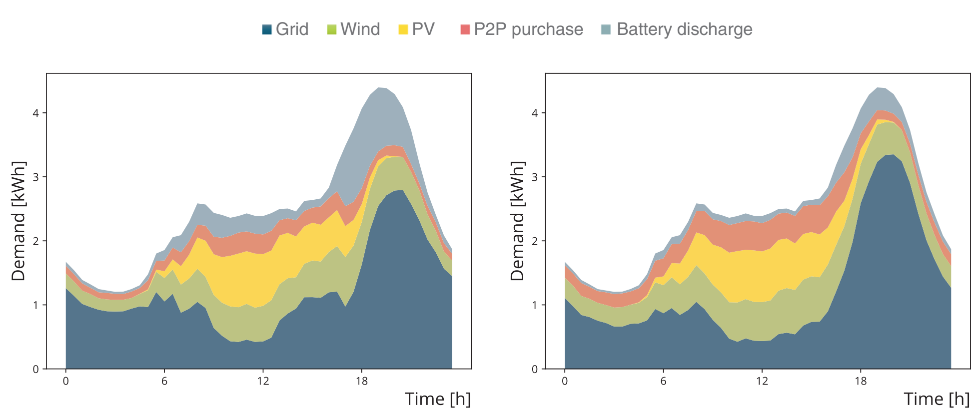
(c) Supply-demand house 3 (d) Supply-demand house 4

Fig. 4. Demand cover for exemplary houses on a day in spring in *Pool Hub* market.

changed the generation and demand profiles of the houses. The choice of houses depicted in this paper is rather conservative with a high energy consumption. Any changes in renewable supply (up or down) will lead to an increase or decrease in savings, respectively. As trade costs do not affect the objective value of the community, the match of aggregated supply and demand influences the results.

Analysing the second factor, we apply the same market design to the different system configurations by introducing prices on the private batteries. In the *Flexi User* market, discharging private storage for one's own demand is assumed to be free for the owner, whereas the common centralised battery has a price assigned to the energy discharged. To be able to compare overall savings in the two designs, we run a test on pricing and compensating private battery usage. The prices assigned to both kinds of storage can, thus, be seen as the investment and operations and maintenance costs of the storage. Running this test, we see a cost increase of about 10% for a setup with decentralised storage in a *Flexi User* market. The change in market design for the setup with a private battery leads to the market being more expensive than then the *Pool Hub*. The difference of below £20 in prices for the exemplary community is for this case study not significant. However, the overall outcome changes notably with the centralised storage being more profitable. The market design is hence a significant driving factor for the two setups and the choice of the right design is crucial.

In this case study, we observe that the two market designs result in large, similar profits for the community when they are applied to the suitable setup. The main insights of testing the two designs can be summarised in:



(a) Average supply-demand Flexi-User (b) Average supply-demand Pool Hub

Fig. 5. Average supply-demand decisions for the two distinct designs in comparison.

Table 4
Overview on the driving factors for the different model outcomes.

		Flexi User	Pool Hub
System configuration	Transmission loss	7.6%	7.6%
	Based on (for):	-P2P trade	-P2P trade -Battery usage
	Battery capacity:	3 × 4 kWh	13.4 kWh
	Battery efficiency:	88.5%	89%
	Battery converter:	2.5 kW	3.3 kW
Market design	Storage accessibility:	Private	common
	Storage price:	–	$p_D^{(t,h)}$, $p_C^{(t)}$
	Trade price:	$p_{P2P}^{(t,h)}$	$p_{P2P}^{(t,h)}$
	Grid feed-in:	No	No

- The overall community profits slightly more from a *Flexi User* as decentralised batteries offer a more flexible utilisation of storage at lower costs.
- A decentralised battery reduces grid consumption the most, while least curtailment happens in a *Pool Hub* market.
- The market design must fit the setup.
- The physical characteristics of commercially available storage entities have only a small influence on the choice of design.
- Storage and P2P trade lower the costs of electricity in all designs.

4.5. Economic viability

Investments in PV, wind and residential batteries are costly, and the consideration of capital costs might significantly influence the presented outcome. The savings in Table 3 outline average reductions in costs of electricity for a nine-months period when P2P trade and batteries are introduced to three sets of communities. Compared to the reference case,[12] a community only needs to invest in battery storage for realising the proposed market designs. Battery storage was estimated to cost US$400 per kWh in 2016 [47], and studies show a further decline – even down to US$200 – within the next decade [48].

To estimate the impact of capital costs, we follow Hirth [49] and calculate each alternative's (NPV) as

$$NPV = -A_0 + \sum_{t=0}^{T} e_t (1+i)^{-t} \tag{13}$$

where A_0 are investment costs, e_t is the return in each period $t \in T$ within the lifetime, and i is the interest rate. We then use

$$g = \frac{i}{1-(1+i)^{-T}} \cdot NPV \tag{14}$$

to turn the *NPV* into annual savings *g*. In the case of a positive *NPV*, the investment pays back within the technology's lifetime. With an assumed interest rate of $i = 5\%$ over a lifetime of $T = 10\ a$ [44], we find a positive *NPV* for the two system setups with 12 kWh and 13.2 kWh of storage, respectively. Table 5 shows the yearly savings over a battery lifetime of 10 years for both market designs based on the estimated capital costs of US$400 per kWh. Operations and maintenance costs are not considered. We also calculated the annual savings for more conservative estimations of capital costs. Batteries achieve in most cases a break-even point and are likely to become affordable.

5. Conclusions

This paper analysed the end-user benefits of electricity storage in the presence of peer-to-peer trade in local electricity markets with smart grid features. We propose two market designs for a community of prosumers incorporating battery storage systems: a *Flexi User* and a *Pool Hub* market. The value of electricity storage and peer-to-peer trade in a community with distributed energy resources and heterogeneous participants, both in demand patterns and technology portfolios, is analysed in detail.

Table 5
Estimation of influence by capital costs.

	Investment costs storage	Savings after investment
Flexi User	3651.3 (£)	768.1 (£/year)
Pool Hub	4016.4 (£)	450.6 (£/year)

Results demonstrate a very interesting trade-off between independence of the main grid and utilisation of the two features added – peer-to-peer trade and storage – for a community of prosumers. In the *Flexi User* case, the overall savings in the community from a combination of storage and peer-to-peer cooperation reaches an electricity bill reduction of 31% compared to a reference case (neither storage nor peer-to-peer trade). While the monetary savings in the *Pool Hub* market add up to 24%, this case entails more direct peer-to-peer trade from distributed energy resources. When putting such local markets into practice, the decision for a certain design is highly contingent upon the desired goal of the local market: energy autarky vs. higher integration of local market features.

Our analysis shows that different system configurations result in similar levels of savings for the electricity end-users. The main driver of the results is the market design. Local market designs must take into account the community setup and its features present. Moreover, each of the two proposed market designs is economically viable: Estimated investment costs for battery storage do decrease but not alter the profitability of the market designs.

To extend and complement the analysis presented in this paper, future research should consider addressing the following points:

(i) A strong driver of the results are the prices for the peer-to-peer trade and the battery usage. Other additional sources and ideas for applicable price schemes as outlined in Fridgen et al. [15] should be explored in more detail.
(ii) Variations of market designs and system configurations: Another market design could, for instance, comprise the possibility of reserving the capacity of a centralised battery for a certain time horizon of e.g. one day. In this way, prosumers can match generation and storage capacity or collectively make use of the arbitrage potential.
(iii) In this paper, we focus exclusively on understanding the operational value of peer-to-peer trade and battery storage as no investment decisions are included in the modelling decisions. We show that a combination of peer-to-peer trade and battery storage gives attractive market-based incentives for investment decisions in local DG. Future research should further elaborate the effect of investment costs and long-term benefits.
(iv) The representation of the community uses a deterministic model which is able to respond to inter-temporal variations of demand and generation. Future research should explore the integration of local electricity markets into the wholesale multi-market regime (intraday and day-ahead). A sequential clearing of a multi-stage decision-making process might show additional contributions from demand side flexibility, especially in association with possible uncertainty about the supply of the distributed energy resources.
(v) The business models presented in this paper concentrate on the end-user benefits of peer-to-peer trade and energy storage. We see that our perception of local markets triggers effects such as demand elasticity that alters the interaction with other parts of the electricity market regime. In further work, the challenges and

[12] The reference case is not a *grid-consumption-only* case, but presumes the existence of renewable energy sources.

effects on established business models as well as on other electricity market participants (e.g. stakeholders and investors) have to be analysed. The impacts of a different sizing of the community and the system-wide implications of a broader implementation of our business models also have to be addressed in the future.

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