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# Design choices in peer-to-peer energy markets with active network management

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**Abstract**

Due to the growing number of Distributed Energy Resources and new electrical loads at the sectoral contact points, novel organisational forms such as Local Energy Markets arise to deal with increasing complexity in the energy system. However, these markets are radically different from traditional energy markets, as they often allow individual prosumers to trade with each other via a peer-to-peer scheme. To guarantee tamper-proof settlement, an increasing number of these markets feature a distributed ledger technology. This paper analyses different design variants of peer-to-peer markets, focusing specifically on the allocation mechanism under network constraints as these mechanisms constitute the core component of a market design. We assess these designs concerning user acceptance, economic performance, practicability, and their ability to relieve grid congestion. Further key performance indicators also cover communal revenues or welfare distribution. For this purpose, we developed an agent-based simulation framework, which builds on data from three German reference municipalities derived from a novel clustering approach. Besides a consolidated presentation of the results, we highlight current implementation obstacles and identify promising concepts for further research.

## 1 | INTRODUCTION

In the face of contemporary global warming, governments operate substantial efforts in the conversion of the energy sector towards renewable resources. The aspiration to become independent of fossil fuels, though, creates new challenges for the energy system's stability. The most prominent tasks are the need to integrate an increasingly decentralised supply structure as well as balancing new volatile energy resources and demand patterns [1]. These transitions do not only embody a challenge in their technical implementation but also with respect to necessary readjustments of the associated energy markets. Thus, large-scale research initiatives were funded to advance the examination of new market approaches, reflecting the needs of a transformed energy system. Yet, we have identified a significant research gap in terms of comprehensive and quantifiable design evaluations for these new markets. Hence, this paper presents a structured and data-based assessment of current design approaches, focussing on allocation mechanisms under network constraints.

### 1.1 | Drivers for new energy markets

Analysing recent developments in this field of study, we can identify three major trends among these new market structures: participation, decentralisation and flexibilisation. To be more precise, participation describes the increasing electricity generation by active prosumers via small-scale renewable plants plus the subsequent trading and sharing of excess energy among them [2]. While participation per se does not feature regional motives, decentralisation focusses on local price building and community-based energy trading [3]. Ultimately, flexibilisation includes new concepts to incentivise gridsupportive behaviour of supply and demand. Specifically, price sensitivities for both consumer-side and producer-side flexibilities are under examination [4].

## 1.2 | New approaches to energy trading

One novel market structure emerging from the trend towards stronger participation are peer-to-peer (P2P) energy markets. As defined by Ref. [2], P2P energy markets comprise 'prosumers equipped with distributed energy resources, [...] able to trade and share energy with each other directly'. Taking stronger emphasis on the system perspective, Tushar et al. [5] argue that the evolvement of P2P energy markets can be traced back to the requirement of integrating an increasing amount of distributed energy resources (DERs) into the energy system. While the participative aspect of production by consumers strongly influences decentralisation, trading among prosumers can theoretically also takes place on a trans-regional level. Conversely, performing electricity trading on a local level does not necessarily involve the direct interaction of peers [6].

Yet, inseparably related to decentralisation is the concept of local energy markets (LEMs). Bjarghov et al. [3] define these markets as 'a tool to decentralise the coordination of participants in a grid, by unifying participants behind a common denominator—local electricity market prices. These market prices aim to facilitate local trade, or in other words, prioritise the exchange of energy resources in smaller spatial distances over larger distances'. Even though this definition highlights the differences to mere P2P markets, in practice as well in most literature, market approaches are both, participative and local [4, 7]. This is also demonstrated by the often substitutable use of the two terms. Henceforth, we use the term LEM for local P2P market approaches.

Despite empowering small-scale prosumers, decentralisation of the energy system leads to an increase in bidirectional power flows and consequently imposes new challenges on grid stability. Therefore, the third major driver for the design of new energy markets is the need for flexibilisation to ensure a stable system. Yet, the possibilities to integrate small-scale producers and demand-side facilities into a cost-based redispatch are limited [8]. That is why researchers examine alternative market-based forms of providing flexibility in addition to the existing cost-based mechanisms [9]. Approaches to providing a more flexible supply and demand structure include price signals, direct market interventions, and new independent flexibility products.

## 1.3 | Related work and contribution

The design of these new market approaches has been further developed and analysed within the last years to successfully implement those concepts in real-world applications. The authors of Ref. [10] analysed the design of such local consumer-centric electricity markets, focussing on nine projects in the DACH + region. They compare different elements of the market design covering pricing and allocation mechanisms. Khorasany et al. [11] focus their work on the performance evaluation of established auction mechanisms for LEMs utilising small synthetic datasets of bids and asks. Another review on current P2P market structures is conducted by the authors in Ref. [12], including a description of optimisation techniques for negotiation and market clearing as well as advantages and challenges that arise with the different market structures. However, in all three studies, mechanisms considering network constraints and flexibility are excluded from the analysis. Ref. [13] compares several market-clearing approaches for P2P markets against different criteria, including scalability, overheads requirements, and network constraints management. A high-level overview of P2P trading frameworks without a detailed discussion of single aspects of market design is presented in Ref. [14]. The authors differentiate between the virtual and the physical layer of P2P trading platforms and point out potential challenges. These include a stable grid operation by complying with voltage and capacity constraints. A more in-depth analysis of the challenges of LEMs, including a review of respective projects, is presented by Ref. [3]. While the paper's focus is on the used modelling approaches and associated distribution grid problems, the authors do not provide a detailed comparison of different design options.

However, the studies mentioned either exclude network constraints from their analysis entirely or avoid using quantifiable criteria to compare competing P2P market designs. Therefore, we argue that in the area of LEM-Design with active network management (ANM), there is a significant demand for further research. ANM, thereby, encompasses the utilisation of flexibilities to eliminate congestion and thus enable reliable operation of the power grid. To fill this research gap, our paper provides an in-depth analysis of various allocation methods featuring distinctive mechanisms for ANM. Ultimately, the study seeks to identify competing market designs in this context and evaluate them according to measurable criteria to provide the reader with an overview of the strengths and weaknesses of the various approaches. For this purpose, the paper makes the following contributions to the scientific discourse:

i. Describing and characterising existing approaches to incorporate ANM into a P2P energy trading scheme based on an extensive literature review.
ii. Selecting appropriate criteria for the assessment of LEMs with ANM and deriving quantifiable Key Performance Indicators (KPIs).
iii. Implementing an agent-based simulation framework using generation and load profiles from real-world communities to evaluate competing market designs.
iv. Assessing the pros and cons of different design variants using simulation results and the defined KPIs plus brief qualitative discussions.

To achieve the proposed contributions, the paper is organised as shown in Figure 1. Within Section 2, where we conduct a comprehensive meta-study on existing P2P markets with ANM, contributions (i.) and (ii.) can be found. Following

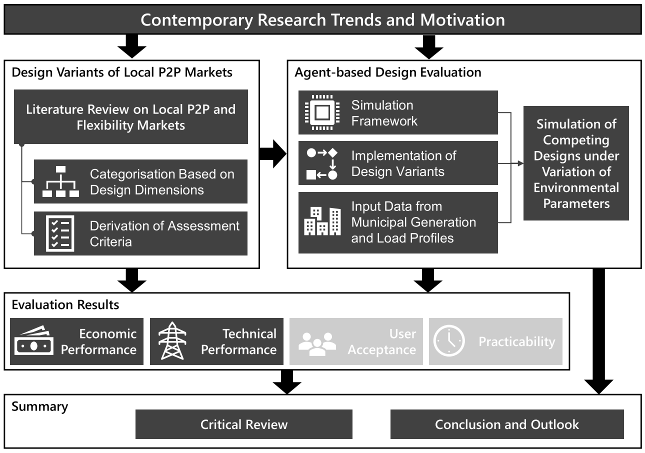


**FIGURE 1** Graphical outline of the paper

that, Section 3 focusses on the implementation of a simulation environment to fulfil (iii.). Then, Section 4 includes the evaluation results and contribution (iv.), before we finish the paper with a discussion on possible methodological shortcomings and our conclusions in the Sections 5 and 6.

## 2 | DESIGN VARIANTS OF LOCAL P2P MARKETS

The primary goal of electricity markets is the cost-optimal allocation of available resources and thus the maximisation of market efficiency [15]. The chosen market design creates uniform and transparent framework conditions for this purpose, facilitating the matching of supply and demand. In this context, the market design defines the trading rules that govern the interaction of market participants. These include, for instance, product definitions, time frame, or price caps [16]. This results in many different design choices, which influence the performance of the market. To further address the challenges related to the decentralisation of the energy system, future market designs should consider existing grid constraints and use available flexibility to facilitate an efficient market outcome.

### 2.1 | Meta-study on existing LEM with ANM

In recent years, research has strongly driven the development of P2P electricity markets as well as local markets for flexibility. To gain an in-depth insight into the design of such markets to date, we examined current projects and research efforts in Germany and internationally as part of a meta-study. Based on the classification of Ref. [17], we differentiated between (1) P2P markets where electricity is traded locally between peers, (2) flexibility markets (FMs) where flexibility as a grid service is offered to system operators or balancing services and (3) markets that combine these two aspects. This review only includes market-based approaches, which enable an active integration of end consumers. Therefore, we excluded concepts focussing on wholesale markets or trading via aggregators. In the case of direct trading of flexibility as a product, all selected markets focus on congestion management in the distribution grid. To cover the latest findings, the projects considered include those that had started within the last 5 years. In total, we analysed 23 approaches, including 12 focussing on P2P electricity trading, six implementing a market for flexibility and four combining these two concepts. To evaluate and compare the implemented market approaches, we developed five categories that cover the essential characteristics of a market design for P2P markets with ANM. These include the implemented allocation mechanism, the price mechanism, the time frame, and the mechanism implemented to consider network constraints. A summary of the results of the meta-study for all 23 markets is shown in Table A1.

#### 2.1.1 | Allocation mechanism

The mechanism used for allocating the available resources represents the core function of any market. In most cases, auction-based methods are implemented to match the market participants' buy and sell orders. For example, authors in Ref. [27] as well as in Ref. [18] and Ref. [29] propose double-sided auctions, enabling both sellers and buyers to place bids on the market. This allows for eliciting price preferences for local renewable energy from the participants as well as actively integrating demand-side flexibility [7]. Ref. [7, 24, 29] implement call auctions using simple order books to collect all bids for one time interval and order them by price for the winner determination. Usually, the order book is arranged inversely. Sell orders are sorted in ascending order and buy orders in descending order. That results in a maximisation of social welfare [15]. However, depending on the objective of the market, a correlated ordering is also possible, as shown in Ref. [39]. The differences between these two options are discussed in more detail in Chapter 4. In the case of FMs, additional information such as sensitivity on the network congestion or restrictions by the flexibility resource is considered in the matching. Therefore, FMs such as ALF [33] or ReFlex [40] use optimisation or respective heuristics with optimal power flow algorithms to assess the ideal flexibility contraction for effectively avoiding grid congestion at the least cost. Schreck et al. [41] integrate such an optimisation-based allocation into a LEM approach to allow the trading of flexibility products such as storage flexibility besides simple sell or buy orders for electricity. Instead of designing such a pool-based market, Etiblogg [20] as well as authors of Ref. [2, 19, 21] use a continuous trading approach that enables bilateral trading between the peers by matching corresponding asks and bids directly. The authors of Ref. [4, 25] focus on the direct trading between the peers without a central coordinator and therefore implement a multi-bilateral trading approach. The authors propose a decentralised trading framework based on simultaneous negotiation over price and energy between all peers, while each market participant is solving their individual optimisation problem [42].

### 2.1.2 | Pricing rule

The price for resources traded on a market depends on the implemented pricing mechanism and is closely related to the chosen allocation method. Uniform pricing is realised by Ref. [18, 24], where the last bid accepted determines the market price. In the case of Ref. [22], the uniform market price is determined by the average of bid and ask prices of all allocated market participants. Ableitner et al. [7] choose a discriminatory pricing strategy, where for each bilateral trade, the price is derived as the mean between the respective buyers' and sellers' price bid. This kind of discriminatory pricing mechanism is also used by markets with continuous trading as in Ref. [21] or [32]. For markets based on multi-bilateral negotiations, individual prices per trading pair may also occur. The final market prices in Ref. [4] or Ref. [25] may differ due to the product differentiation introduced, for example, according to the origin of electricity. If there is no such differentiation, the prices of the individual trading pairs converge to a common value in these markets [43]. In the case of flexibility trading, nearly all analysed markets choose a discriminatory pricing rule, paying flexibility providers their bidding price. This allows them to consider the non-homogeneous nature of flexibility products [33]. Only Ref. [34] implements a uniform pricing mechanism to determine the final market price. Additionally, Zhang et al. [31] and the Cornwall LEM [34] implement a capacity pricing for secured capacity bought as an option that can be requested by the system operator when needed.

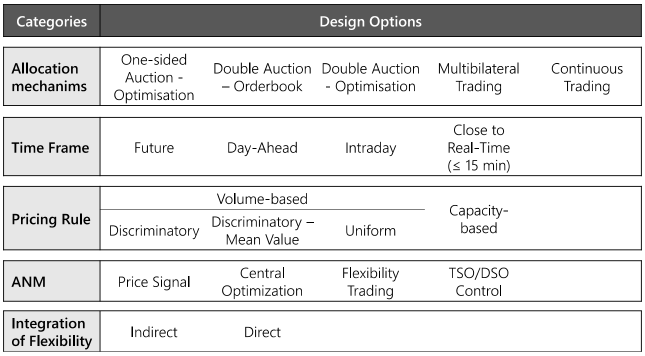
### 2.1.3 | Time frame

In most of the analysed P2P electricity markets allocation takes place up to ≤15 min before delivery [21, 24, 27]. Orlandini et al. [4] allow trading until 5 min before the physical delivery. Such trading close to real-time reduces the risk of uncertainty concerning energy production from renewable energies as well as energy demand. Schreck et al. [41] set up a day-ahead auction clearing every hour for the next day being able to consider time-coupled flexible loads. Morstyn et al. [25] combine such a day-ahead auction with an intraday auction to accommodate uncertainties and balance the portfolio. In most of the considered markets, trading flexibility is either done day-ahead or intraday. The authors in Ref. [30] set up a market close to real-time for the trading of energy and flexibility. Zeiselmair et al. [33, 34] complement the short-term products with long-term contraction, which can be activated by the system operator on demand.

### 2.1.4 | Consideration of network constraints

To ensure a secure and efficient system, future market designs should consider existing network constraints to contribute to an optimised grid operation. Different approaches are currently discussed to avoid grid congestions caused by P2P trading. Ref. [19, 21] are addressing this issue by involving the network operator in the P2P clearing process to validate the transactions based on the network condition. In case of a critical network situation, peers can be blocked from trading by the network operator. Kim et al. [23] implement a P2P market based on transaction zoning considering network constraints. Based on network calculation, the market is divided into different trading zones. Available capacity between the zones is traded in a separate auction. Markets using a central optimisation for allocation as in Ref. [41] can include grid parameters as restrictions in the optimisation algorithm and therefore ensure that the market outcome is not violating any grid constraint. Ref. [22, 25] choose a more decentralised way by introducing an external price signal as a coordinating element between the market and the grid. The authors of Ref. [25], therefore, calculate day-ahead Locational Marginal Prices (LMP), which are then considered in the P2P trading process, penalising peers according to their grid usage. Khorasany [22] calculate a subscription charge based on the power transfer distribution factor (PTDF). For a line with predicted overload, this charge is increased to reduce the possibility of overload. Orlandini et al. [4] follow a similar strategy by calculating individual grid tariffs for peers in case of grid congestion. Therefore, in the first step, the grid operator validates the clearing results of the P2P market using an AC power flow model (AC-PF). In the case of grid congestion, a grid tariff for the bilateral trades that cause the grid congestion is calculated. Then, the iterative process returns to clearing the P2P market with the updated grid tariffs. In contrast to the mechanisms mentioned so far, which directly consider grid restrictions in the P2P energy trading, additional FMs along with P2P energy trading allow for corrective measures in case of network congestion. Based on the results of preceding energy markets, the system operator estimates its demand for flexibility, which is then procured on the local FM. Ref. [32] or [30] examine such an interactive market design for P2P energy trading and FMs.

To conclude the results from the meta-study, various design options exist for P2P energy markets with ANM. Decentralised approaches prioritise the direct interaction among the peers as well as the fulfilment of their individual preferences. On the other hand, centralised approaches mainly focus on the achievement of a global objective such as maximising social welfare or improving system stability and congestion management. When considering flexibility in trading, central optimisation techniques are used to clear the market while respecting existing constraints and requirements. In general, mechanisms to avoid grid congestion can be distinguished by the degree of influence by the grid operator on market processes. The involvement of system operators (DSO or TSO) varies from indirect coordination via individual network charges to direct intervention in the trading transactions as well as being responsible for the clearing process. Looking at the temporal dimension, markets close to real-time have the advantage of reducing uncertainty concerning energy production from renewable energies and energy demand. This is particularly important, given the high share of renewable energies in LEMs [31]. Figure 2 summarises the identified design options for all four categories in a morphological box, although not all combinations necessarily constitute a sensible design choice for a



| Categories | Design Options | | | | |
|---|---|---|---|---|---|
| Allocation mechanims | One-sided Auction - Optimisation | Double Auction – Orderbook | Double Auction - Optimisation | Multibilateral Trading | Continuous Trading |
| Time Frame | Future | Day-Ahead | Intraday | Close to Real-Time (≤ 15 min) | |
| Pricing Rule | Volume-based<br>Discriminatory | Volume-based<br>Discriminatory – Mean Value | Volume-based<br>Uniform | Capacity-based | |
| ANM | Price Signal | Central Optimization | Flexibility Trading | TSO/DSO Control | |
| Integration of Flexibility | Indirect | Direct | | | |

**FIGURE 2** Morphological box on design variants

P2P market with ANM. Hence, from Figure 1, we derived four feasible configurations that could be identified from the meta-study and will be implemented in Section 3.2 for further evaluation. However, as local conditions and project objectives can vary, these variants might not be suited in some use cases. Instead, market designs are often tailored directly to the requirements and may therefore deviate in one or more criteria.

## 2.2 | KPIs

Based on the requirements for P2P markets with ANM, nine criteria were developed to evaluate and compare the performance of the possible market designs. The assessment considers economic and technical performance, user requirements, as well as practical feasibility. Figure 3 summarises the evaluation criteria. Where appropriate, we used a quantitative analysis of the simulation results to evaluate economic and technical performance. For user acceptance and practicability criteria, which are difficult to assess with the chosen simulation approach, we instead included brief qualitative discussions.

### 2.2.1 | Economic performance

From an economic perspective, electricity markets should be designed to provide electricity at the lowest economic cost, by making optimal use of existing resources [15].

*Gross profit increase*

To evaluate the economic performance of the different market designs, we examine the average transaction price and the additional communal gross profit from P2P trading. This communal gross profit increase $\Delta\pi$ is defined as the realised cost-savings for consumers and additional revenues for producers compared to traditional electricity procurement $P_{\text{ret}}$ via a retailer at the price $\lambda_{\text{ret}}$ and regulatory feed-in tariff $\lambda_{\text{exp}}$ for surplus electricity $P_{\text{exp}}$.

$$\Delta\pi = \frac{(P_{\text{exp}} - P_{\text{P2P}})\lambda_{\text{exp}} - (P_{\text{ret}} - P_{\text{P2P}})\lambda_{\text{ret}}}{P_{\text{exp}}\lambda_{\text{exp}} - P_{\text{ret}}\lambda_{\text{ret}}} \tag{1}$$

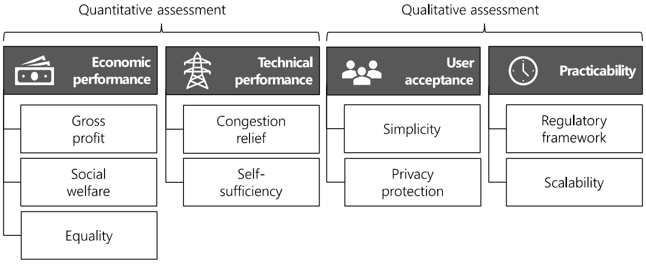


**FIGURE 3** KPIs

*Social welfare*

For a comprehensive analysis of the economic performance, we further evaluate the social welfare $\omega$ of the different allocation methods. Social welfare can be defined as the sum of the payoffs or utilities of sellers $\mathcal{S}$ and buyers $\mathcal{B}$ calculated by the difference between the willingness to sell or buy and the realised market price $\lambda_{\text{P2P}}$ [44].

$$\omega = \sum_{s \in \mathcal{S}} P_s(\lambda_{\text{P2P}} - \lambda_s) + \sum_{b \in \mathcal{B}} P_b(\lambda_b - \lambda_{\text{P2P}}) \tag{2}$$

*Equality*

Equality among market participants is an important aspect of the long-term success of the market platform and is often a key factor in a holistic welfare definition. Great inequality in terms of cost and revenues can lead to dissatisfaction among peers. To evaluate this criterion, we adapted the equality index $\epsilon$ from Ref. [45], to measure the income distribution among all peers $N$. To compensate for the advantage of large generation plants over mere consumers, we based the index only on the individual gross profit increase that arises from P2P trading compared to the reference case.

$$\epsilon = \frac{\sum_{n=1}^{N}\sum_{m=1}^{N}|\Delta\pi_n - \Delta\pi_m|}{2N\sum_{n=1}^{N}\Delta\pi_n} \tag{3}$$

### 2.2.2 | Technical performance

One main goal of the examined P2P trading with ANM is the balance of local demand and supply in consideration of existing network restrictions. The fulfilment of this goal is evaluated by the following two criteria.

*Congestion relief efficiency*

With this criterion $\gamma$, we evaluate the effectiveness of the chosen mechanism to prevent network congestion. As mechanisms vary from monetary incentives to adopt P2P trading activities to downstream corrective measures, a universally valid performance indicator must be found that takes these conceptual differences into fair account. As a suitable criterion, we have defined the P2P revenue losses and the decrease in welfare that are necessary to eliminate occurring congestion by reducing the line load $P_{\text{Line}}$ in question.

$$\gamma_p = \frac{\Delta P_{\text{P2P}}}{\Delta P_{\text{Line}}} \quad \text{and} \quad \gamma_w = \frac{\Delta \omega}{\Delta P_{\text{Line}}} \tag{4}$$

*Self-sufficiency*
As a second technical criterion, we measure how much local demand is supplied by local generation, indicating the self-sufficiency of the local P2P market and the surrounding grid load. The metric of independency $\tau$ is defined as the energy traded at the P2P market divided by the total energy demand from prosumers in the P2P market.

$$\tau = \frac{\sum P_{\text{P2P}}}{\sum P_{\text{P2P}} + \sum P_{\text{retail}}} \tag{5}$$

### 2.2.3 | User acceptance

A key factor for the successful implementation of LEMs is the acceptance by the potential users of the platform and thus their willingness to participate [27]. Hence, the following two criteria were defined to be critical for high user acceptance.

*Simplicity*
Most potential users have little knowledge of the function of electricity markets. To encourage participation, it is necessary to reduce complexity and ensure high transparency and traceability of the market processes.

*Privacy protection*
Individual energy consumption and related price preferences are sensitive personal data that need to be protected. The more information participants share with the platform or other peers, the greater the concerns about data security.

### 2.2.4 | Practicability

For a real-world implementation of a P2P market, two crucial aspects to be considered are the alignment with existing regulation and the scalability of the concept.

*Regulatory framework*
The considered local P2P markets are aiming at improving the coordination between the electricity market and the underlying grid. Hence, an assessment of regulatory compliance in this area is needed. This includes the German unbundling regulation as well as the incentive regulation for system operators and the tariff structure based on it [46].

*Scalability*
Due to the high number of potential participants in P2P trading, the computational and communication requirements associated with the market concept are important aspects to be considered [47]. To ensure scalability, computational complexity and communication expenses should be minimised.

# 3 | AGENT-BASED DESIGN EVALUATION

To underpin the methodology with real-world data and allow for a quantifiable evaluation of KPIs at decisive points, we developed a streamlined agent-based simulation framework. This framework offers two key advantages over empirical analysis. First, it allows the comparison of different market designs against each other under fixed conditions. Second, it enables the selective variation of design and environmental parameters to test their influence on the market outcome.

## 3.1 | Simulation environment

The established simulation environment uses several energy-related master data, including the German census dataset, federal energy registers, and other input parameters, as described in detail by Bogensperger et al. [48]. Given a unique municipality-identifier, the framework constructs a digital twin of the community, containing data of the individual buildings and generation facilities on site. From there, we treat all these objects as individual agents trying to balance their residual load by engaging in the local P2P trade. Only if they fail to cover their demand or to sell surplus electricity locally, the agents resort to backup solutions. These include procurement via a retail supplier or feeding electricity back to the grid at the current intraday price, respectively. Market clearing is calculated in hourly time steps so that power and traded energy quantities can be equated in the evaluation. In addition, forecast uncertainties and inter-temporal dependencies are not considered, so sensitivities concerning the market time frame are not part of the quantitative analysis. Figure 4 depicts the load profile and market behaviour of a PV-dominated municipality for 1 week.

Assuming perfect market turnover, we can identify a 100% priority for P2P trades within the community over external sales and purchases. The backup options thus represent an

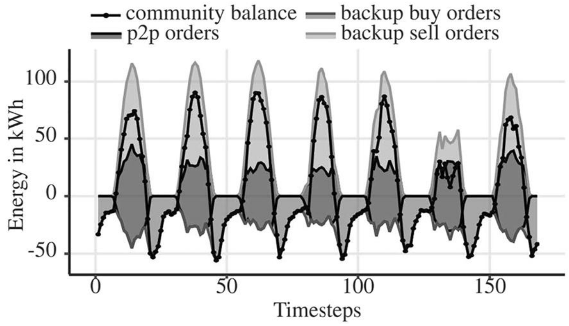


**FIGURE 4** Energy balance and P2P-turnover within sample community

upper and lower bound for the pricing of P2P trading and define the viable trading corridor. To illustrate and simplify the case, we factored out any taxes and surcharges in our analysis. Thus, procurements via the retailer are 7.06 ct/kWh, which is significantly lower than the usual household electricity prices in Germany. Additionally, the resulting average buyer price in the P2P market is identical to the seller price at every time step, as no money flows to third parties such as the platform operator. Depending on the chosen allocation approach, an average price will emerge in the P2P market that moves within this corridor and reflects the dynamic ratio between supply and demand, as shown in Figure 5.

For the sake of simplicity and transparency, we decided to implement the agents as zero intelligence (ZI) traders in the first step. Hence, their bids $\lambda_b \in \Lambda_b$ and asks $\lambda_s \in \Lambda_s$ follow a normal distribution $\mathcal{N}$ between the borders of the trading corridor, with the respective $\mu$ values lying exactly between retail and export tariffs and $\sigma$ covering the entire interval. Only for market designs with open order-books, the peers may adjust their bids based on previous transactions [21].

$$\Lambda_b, \Lambda_s = \mathcal{N}(0.5; 0.5) \cdot \left(\lambda_{\text{retail}} - \lambda_{\text{export}}\right) \tag{6}$$

While the residual load profiles of individual buildings can be generated from real-world data, the simulation environment at its current state lacks information about grid topology in the communities of interest. Therefore, we have adopted a highly simplified network graph consisting of two vertices and one connecting edge for all municipalities. This simplification, which was adapted from Ref. [42], allows the analysis of a generic congestion situation with one export and one import constraint node but without the need for complex network calculations. Within this setting, we implemented artificial grid constraints in the analysis to evaluate the ability of different market designs to resolve grid congestion.

The simulation environment was implemented in Python and relies heavily on the Mesa agent-based modelling framework [49]. Optimisation problems were linearised and expressed in standard form so that we could resort to the open-source SciPy [50] interface for linear programming with an interior point solver. Algorithms of this type are certain to produce strictly complimentary solutions for bounded linear problems [51].

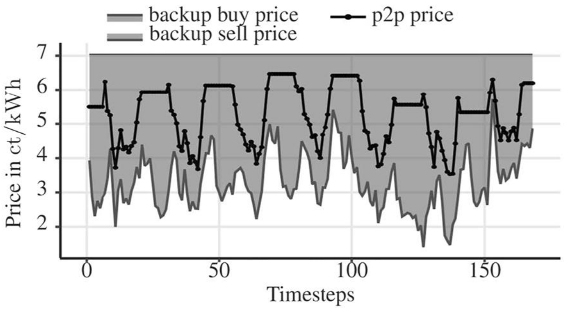


**FIGURE 5** Trading corridor and average P2P price

## 3.2 | Implementation of selected design variants

In addition to the simulation environment, a comparative analysis of design variants also requires their simulative implementation. Rather than replicating all conceivable designs from Section 2.1 in their full degree of detail, the following implementations are intended to specifically embody the different approaches to allocation mechanisms and ANM that emerged from the meta-study. Thus, the following four design variants, implemented for in-depth evaluation, are our interpretation of the various basic concepts and do not necessarily depict existing approaches exactly. The variation of other design dimensions within the scope of Figure 2 may lead to further sub-variants of the same core concept. This approach also makes it possible to isolate the effects of key design decisions within the later evaluation. Within the result of Section 4, we refer to the variants via their distinct two-letter identifiers, found in Sections 3.2.1–3.2.4.

### 3.2.1 | Continuous trade with zonal splits (ZN)

In this peer-centric market set-up, participants bid in an initially unrestricted continuous trade, where bilateral contracts between the peers are executed. Therefore, prices differ between each individual trade. However, since the agent-based modelling framework relies on discrete time steps, the continuous bidding behaviour is emulated by a random sorting of the order book. Each time two bids are matched, the grid operator examines the condition of the electricity grid. Transactions that result in the load limits being exceeded cannot be executed and are therefore blocked by the system operator. For the 2-node simulation framework, each additional buyer–seller transaction $P_{b,s}$ must not violate the load limit $\overline{P}$ between node $\Theta$ and node $\Phi$.

$$\sum P_{\Theta,\Phi} + P_{b,s} \leq \left|\overline{P}_{\Theta,\Phi}\right| \tag{7}$$

As a result, the market is divided into individual bidding zones during the period in which there is a risk of congestion so that trading can only take place within the zones. Trades that alleviate congestion remain feasible. The spatial division of the market area is correspondingly dynamic and changes depending on the grid situation.

### 3.2.2 | Downstream flexibility market

Instead of restricting the P2P trading in case of predicted congestion, market results can be corrected afterwards by introducing an FM. After the P2P market has been cleared via an auction mechanism, the network operator examines the area for any network congestion that may occur. If a critical grid situation arises, an FM is established with a corresponding demand for flexibility to counteract the congestion. Depending on the grid situation, a demand is placed for an active power adjustment by the participants in positive or negative direction. Table 1 illustrates the flexibility demand for a situation where Θ embodies the export constraint node and Φ the import constraint node. For the opposite congestion situation, the signs are reversed accordingly.

To resolve occurring congestion in a cost-optimal way, the allocation mechanism selects the most favourable flexibility offers (FO) according to the scheme above. Cost optimality is achieved by formulating an optimisation problem with many possible constraints, as described in detail in Ref. [33]. For this purpose, each FO must be assigned a specific price for up-dispatch $\lambda_{\text{flex}}^{+}$ and down-dispatch $\lambda_{\text{flex}}^{-}$, respectively. For simplicity, rather than introducing additional assumptions regarding the price sensitivity of the flexible peers, we correlated the specific redispatch costs with the initial bidding behaviour in the P2P market. For the model, we postulate that a high bid in the P2P market entails low flexibility and thus a high down-dispatch price. On the seller's side, the same applies to a low sales price, accordingly, while the exact opposite is the case for the up-dispatch prices. However, as all FOs embody a deviation from schedule, every action on the FM violates the previously reached P2P agreements [32]. FOs can, therefore, not be considered in isolation but are always entangled with a complimentary offer from the other side of the market. That implies that an initially favourable redispatch offer can involve an expensive counterpart. To solve this entanglement, we introduced a constraint that ensures that power changes at one node are balanced at the other node.

$$\sum_{\mathrm{B,S}} \Delta P_{b,s,\Theta} = -1 \cdot \sum_{\mathrm{B,S}} \Delta P_{b,s,\Phi} \tag{8}$$

In contrast to the traditional redispatch scheme, where down-dispatch in production is mirrored with up-dispatch on the opposite congestion side, the consideration of loads allows for various configurations, including down-dispatch production plus down-dispatch consumption. By (8), the costs of entanglement can be directly priced into the allocation mechanism of the FM. After determining the flexible power adjustments, the original market result with the now updated bids and asks is revised accordingly.

### 3.2.3 | Pool-based auction with price signals

Instead of revising the P2P market result afterwards, in this case, a locally differentiated price signal $C_{b,s}$ is assigned to each potential P2P trading pair. Hence, the costs of grid use are directly incorporated into P2P trading as a coordinating element. While these price signals can be derived from forecasts and LMP-formulations [25, 51], this does not guarantee conclusive congestion relief. Instead, replicating Orlandini et al.'s approach [4], we have integrated a line-search algorithm for the allocation mechanism, which optimises $C_{b,s}$ until the power flow between the nodes Θ and Φ complies with the grid-side specifications. The flowchart of this mechanism is displayed in Figure 6.

### 3.2.4 | Central dispatch optimisation

The following section provides an insight into market optimisation via a central dispatch algorithm. The outlined objective function and constraints are, in our view, the minimum requirements for describing the mechanism as a linear optimisation

**TABLE 1** Flexibility demand for opposite congestion situations

| | Export constraint node: Θ | | Export constraint node: Φ | |
|---|---|---|---|---|
| | **Import constraint node: Φ** | | **Import constraint node: Θ** | |
| Buyers | $\Delta P_{b,\Theta}^{+}$ | $\Delta P_{b,\phi}^{-}$ | $\Delta P_{b,\Theta}^{-}$ | $\Delta P_{b,\phi}^{+}$ |
| Sellers | $\Delta P_{b,\Theta}^{-}$ | $\Delta P_{b,\phi}^{+}$ | $\Delta P_{b,\Theta}^{+}$ | $\Delta P_{b,\phi}^{-}$ |

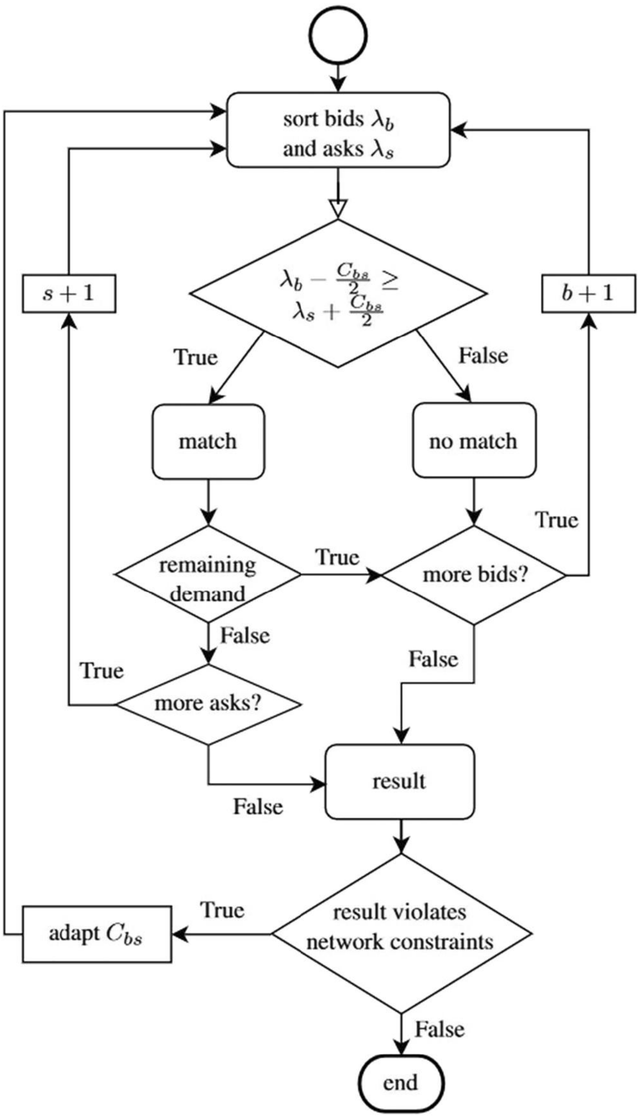


**FIGURE 6** Flowchart of a pool-based market design with price signals

model. The optimisation objective (9a) includes the costs of the entire community taking into account both the costs for electric power (or energy) $C_{\text{Power}}$ and the flexibility cost $C_{\text{Flexibility}}$.

$$\min C_{\text{Power}} + \sum_{n\in N} C_{n,\text{Flexibility}} \tag{9a}$$

By drawing the assessment limits around the entire community, the individual losses and revenues among the peers cancel each other out. What instead determines the communal energy costs (9b) are only the procurement of all buyers via a retail supplier and the seller's electricity export to the local grid. Electricity production costs of renewable DERs are neglected in this case.

$$C_{\text{Power}} = \sum_{b\in\mathcal{B}} P_{b,\text{retail}}\,\lambda_{\text{retail}} - \sum_{s\in\mathcal{S}} P_{s,\text{export}}\,\lambda_{\text{export}} \tag{9b}$$

For flexibility costs, on the other hand, it is necessary to add up the costs of the individual peers, both buyers and sellers. These result from the power balance $P_n$ minus the given specified residual load (or supply for sellers) $R_n$ multiplied by the redispatch prices $\lambda^{\pm}_{n,\text{flex}}$ associated with this difference. The case distinction in (9c) and (9d) is necessary to account for diverging costs for up- and down-dispatch. Constraint (9e) ensures that the flexible power adjustment remains within the peers' individual specifications. The total power flow of a peer $P_n$ is calculated via the sum of the traded power with the respective opposite market side (buyers or sellers).

$$C_{n,\text{Flexibility}} \geq \lambda^{+}_{n,\text{flex}}(P_n - R_n) \;\; \forall \;\; n \in \mathcal{N} \tag{9c}$$

$$C_{n,\text{Flexibility}} \geq -\lambda^{-}_{n,\text{flex}}(P_n - R_n) \;\; \forall \;\; n \in \mathcal{N} \tag{9d}$$

$$P_n^{\min} \leq P_n \leq P_n^{\max} \quad \forall \;\; n \in \mathcal{N} \tag{9e}$$

$$P_n = \sum_{b\in\mathcal{B}} P_{b,s} \quad \forall \;\; s \in \mathcal{S} \tag{9f}$$

$$P_n = \sum_{s\in\mathcal{S}} P_{b,s} \quad \forall \;\; b \in \mathcal{B} \tag{9g}$$

Constraint (9h) restricts the possible power flows based on the compatibility of bids and asks. Only those transactions are allowed where the purchase price exceeds the sale price.

$$P_{b,s} = 0 \;\; \forall \;\; \lambda_{s\in\mathcal{S}} > \lambda_{b\in\mathcal{B}} \tag{9h}$$

With constraints (9i) and (9j), the network restrictions $\overline{P}_{\text{Line}}$ between the two nodes are enforced. In a simplified two-node model, it is sufficient to evaluate the power balance of one vertex to determine the resulting network load of the interconnecting grid. Therefore, the constraints summarise all power flows running from node $\Theta$ to node $\Phi$. The case distinction is necessary to solve a constraint originally involving a modulus using well-established linear programming approaches.

$$\sum_{s\in\Theta}\sum_{b\in\Phi} P_{b,s} - \sum_{b\in\Theta}\sum_{s\in\Phi} P_{b,s} \geq -\overline{P}_{\text{Line}} \tag{9i}$$

$$\sum_{s\in\Theta}\sum_{b\in\Phi} P_{b,s} - \sum_{b\in\Theta}\sum_{s\in\Phi} P_{b,s} \leq \overline{P}_{\text{Line}} \tag{9j}$$

Since the power flows as decision variables do not contain directional information, the decision variables only include the traded quantities between the pairs. Therefore, all buying and selling transactions are inextricably linked. In addition, however, it is crucial to restrict the solution space to positive values with (9k).

$$P_{b,s} \geq 0 \tag{9k}$$

## 4 | EVALUATION RESULTS

The following section presents the results of the market design analysis and uses simulation results to support further evidence where appropriate. We first evaluate the sensitivities of the individual design dimensions concerning the KPIs presented before a comprehensive evaluation of the four selected design variants from Figure 2, which is shown in Section 4.4. As a data basis, we selected three German municipalities that emerged as cluster representatives from the unsupervised clustering derived in Ref. [52]. Therefore, the selected municipalities from Table 2 represent three out of 20 German municipal clusters with regard to 27 distinct features ranging from the number of buildings, installed renewable capacities to their degree of energy autarky, and the local supply and demand ratio over the year 2017.

### 4.1 | Economic evaluation of allocation mechanisms

To evaluate the market performance and accurately extract the sensitivities of individual design dimensions, we have implemented further sub-variants in addition to the variants presented in Section 3.2. These variants focus exclusively on the P2P allocation mechanism and do not consider occurring congestion for the time being.

- UN: Double-sided call auction with uniform market-clearing price.

**TABLE 2** Key facts of selected sample municipalities

| | Henschtal | Loebitz | Krummwisch |
|---|---|---|---|
| No. of buildings | 98 | 81 | 107 |
| Installed PV | 0.17 MW | 0.14 MW | 0.18 MW |
| Installed wind | 0 MW | 8 MW | 0 MW |
| Installed Bio | 0 MW | 0 MW | 0.25 MW |
| Degree of Autarky | 28% | 97% | 33% |
| Supply demand ratio | 0.56 | 128 | 1.22 |

- DR: Double-sided call auction with discriminatory pricing scheme; reverse order book arrangement.
- CC: Continuous trading with closed order book.
- CO: Continuous trading with open order book allowing agents to adjust their prices based on previous transactions [21].
- DC: Double-sided call auction with discriminatory pricing scheme; correlating order book arrangement [39].
- OP: Central optimisation routine matching bids and asks to maximise P2P revenue.

For these allocation variants, the average communal P2P price is displayed in Figure 7 together with the results for alternative pricing mechanisms based on the mid-market rate (MM) and the supply and demand ratio (SD) adapted from Ref. [48].

For the uniform pricing scheme, the largest price fluctuations within the community can be observed. In a discriminatory pricing scheme, these fluctuations are reduced, whereby this effect is most pronounced with a correlating order book arrangement. Allowing dynamic bid and ask adjustments via an open order book leads to an increased price level in all three communities compared to a closed auction. The higher the resulting average price, the more attractive an allocation mechanism is for producers. This can be beneficial for stimulating the construction of new DERs in the area, but it can also increase social inequalities.

### 4.1.1 | Communal gross profit

Evaluating the communal gross profit for various allocation mechanisms exposes significant differences in economic performance for the selected design variants. While the energy surplus in Loebitz is too large to visually represent the comparatively small P2P benefits, Figure 8 shows a profit increase for Krummwisch of nearly 35% depending on the allocation method chosen.

While a uniform pricing scheme and a reversely arranged call auction are on par regarding their economic efficiency, the advantages of discriminatory pricing become evident when bids and asks are arranged correlatingly in the order book. This arrangement allows matching additional pairs of buyers and sellers beyond a uniform market-clearing price to further increase P2P revenue. Efficiency-wise, continuous trading is positioned between these two variants. Since there is no arrangement of bids and asks as in call auctions, but instead, the next best offers are matched instantaneous, continuous trading is unsuited to maximise P2P revenue. This disadvantage can be partially compensated for by a public order book with the possibility of dynamic price adjustments at the expense of statistically higher price levels. However, this possibility also applies to call auctions so that the agents can adjust their bids for the next trading period to optimise their revenue.

Since forecast uncertainties are not considered in the model, no quantifiable statements can be made regarding the influence of the allocation methods' time frame. However, it can be assumed that the optimality of the market-clearing increases the closer it is executed to the delivery period. In return, the planning certainty of the market participants is reduced likewise. With regard to central dispatch optimisation methods, the result can be further improved as the allocation covers multiple adjacent delivery periods and inter-temporal dependencies such as storage levels are considered in the optimisation [33].

### 4.1.2 | Social welfare

Concerning communities' overall social welfare, the findings are exactly reversed in comparison to the gross profit analysis. Figure 9 displays that for uniform pricing and

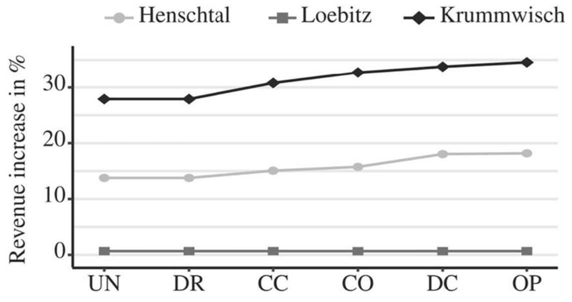


**FIGURE 8** Communal gross profit increase in relation to implemented P2P trading mechanism

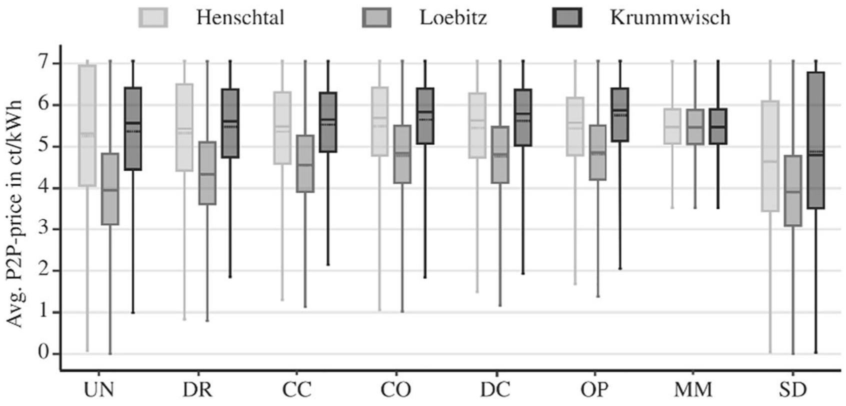


**FIGURE 7** Average communal P2P price for different allocation and pricing mechanisms

discriminatory pricing when bids and asks are arranged in opposite directions, the agents' welfare is maximised. While various markets from the meta-study are undertaking social welfare optimisation [18, 28, 41], we would argue that this objective sacrifices revenue and liquidity of the P2P market. In this case, while some peers may enjoy greater payoffs, the community's overall gross profits decline, and it becomes more dependent on energy exchange with the surrounding grid.

#### 4.1.3 | Equality index

Concerning equality within the communities, the simulation results are less definite than the analyses on economic efficiency. As shown in Figure 10, there exist strong dependencies on regional circumstances. As expected, the mere introduction of a discriminatory pricing scheme leads to a less equal revenue distribution with a uniform market-clearing price. However, if the order book arrangement is adjusted to optimise turnover as in DC, this cancels out the disadvantage to a certain extent, as more possible traders can participate in the market in the first place.

For closed and open continuous trading, the findings are ambiguous. In Henschtal and Krumwisch, where a relatively balanced ratio of prosumers and consumers prevails, a significant equality advantage compared to the reverse call auction can be observed. This can be attributed to the fact that within continuous trading, bidding time is implemented as a random variable that distributes the matched bids more evenly in the long run. However, whether the order book is open or closed makes little difference in this case. In Loebitz, this effect is not noticeable, as most of the electricity generation can be attributed to only four wind turbines. If these generators, however, harmonise their asks due to insight into the open order book, the total communal equality increases in this case.

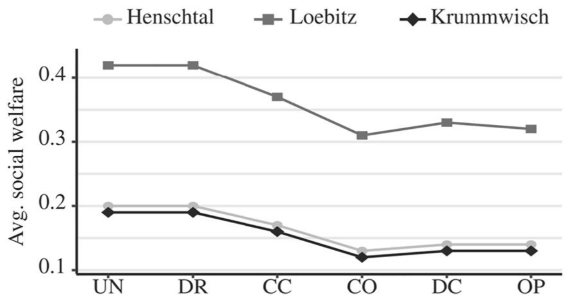


**FIGURE 9** Average social welfare for different allocation mechanisms and communities

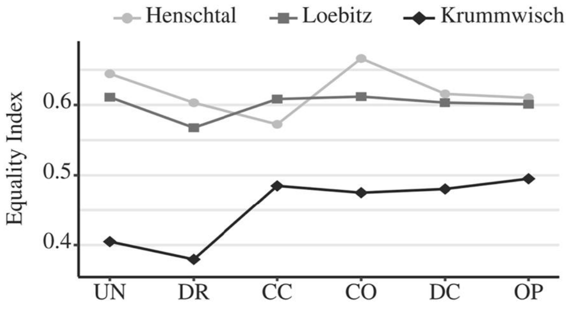


**FIGURE 10** Equality index for different communities and allocation mechanisms

### 4.2 | Technical evaluation of allocation mechanisms

The technical evaluation of the allocation mechanisms focusses on the effects of P2P trading on the power grid load. In the following, we will distinguish between loads on the surrounding grid caused by energy imports and exports across municipal borders and congestion within the municipal area.

#### 4.2.1 | Self-sufficiency

As the municipal self-sufficiency rate, such as the municipal gross profit, is calculated from the revenue of P2P trading, a strong correlation can be observed between the two indices. Allocation mechanisms with good economic performance are, therefore, at the same time beneficial for the surrounding power grid, as a larger proportion of the demand can be served regionally. Hence, the figures from Table 3 reflect the proportions from Figure 8. However, they fall short of the autarky measures from Table 2, as depending on the agents' price expectations, not all bids can be realised.

#### 4.2.2 | Congestion relief efficiency

To analyse the mechanisms in terms of their congestion relief efficiency, we evaluate the resulting loss in economic performance according to Section 2.2.2. For this purpose, a market allocation is first carried out without network restrictions before synthetic congestion is created between the network nodes $\Theta$ and $\Phi$ under otherwise identical conditions. Figure 11 shows that all approaches can solve bottlenecks without causing efficiency losses of more than 3.5% compared to the unrestricted P2P market result.

Since central dispatch CD explicitly optimises community revenue, this variant can be considered a lower bound for revenue losses in this regard. The revenue losses are comparatively small because only in rare cases do supply and demand come close to balancing each other. In times of over-

**TABLE 3** Self-sufficiency rate for different allocation mechanisms and communities

| | UN | DR | CC | CO | DC | OP |
|---|---|---|---|---|---|---|
| Henschtal | 0.21 | 0.21 | 0.23 | 0.24 | 0.27 | 0.27 |
| Loebitz | 0.95 | 0.95 | 0.95 | 0.94 | 0.95 | 0.95 |
| Krummwisch | 0.23 | 0.23 | 0.25 | 0.27 | 0.28 | 0.28 |

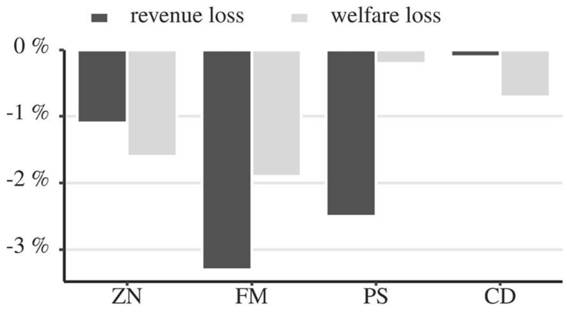


**FIGURE 11** Congestion relief efficiency regarding P2P revenue and welfare for Henschtal

or undersupply, the matching algorithm can easily adjust the P2P market result by accessing other peers willing to trade whose bids and asks on the P2P market have a relieving effect on the power grid. However, this process comes at the cost of welfare, where auction designs with price signals PS are the best option. In this case, the specific costs $c_{b,s}$ lead to fewer bids and asks being matched that are close in price. However, the welfare benefit for the peers only materialises if the mechanism uses only virtual price signals without an actual payment by the peers. Otherwise, the system operator benefits from these mark-ups instead of the peers. In terms of revenue losses, PS is inferior to the zonal splits ZN, because the adjustment of $C_{b,s}$ often shifts the market structure more than necessary to resolve congestion if several peers offer at the same price. In our scenario, this especially affects those peers who bid at the edge of the trading corridor and thus simultaneously enter the market when the network costs are adjusted to a certain extent. Yet, in simulations with more complex grid topologies or different bidding behaviours, this effect might quickly obliterate. Since in the downstream FM, the previous P2P result has to be revised in case of congestion, we observe the poorest efficiency concerning both criteria. This behaviour can be visualised as a greedy algorithm running into a local optimum, which is hard to escape once network restrictions are imposed. Integrated mechanisms consider all constraints already in the market-clearing step and therefore do not face this issue.

## 4.3 | Qualitative discussion regarding user acceptance and practicability

### 4.3.1 | Simplicity

Continuous trading based on the first-come-first-served principle combined with pay-as-bid pricing is a simple allocation mechanism that offers high transparency concerning trading partners and prices. Implementing a call auction reduces autonomy for peers as a central coordinator is responsible for the allocation. However, a distinction can be made whether a simple order book mechanism is applied or an optimisation algorithm is used for the market clearing. The latter is used when considering grid constraints as well as technical boundary conditions of flexibilities, which increases the complexity of the allocation. As soon as prices are further differentiated depending on the grid situation, price dynamics are hard to understand for market participants. Therefore, ensuring transparency and easy market access is challenging when considering the grid situation in LEMs.

### 4.3.2 | Privacy protection

Privacy issues arise when open order books are implemented and individual energy consumption/production patterns, as well as price preferences, become public as in continuous trading. Market participants can infer the individual consumption behaviour of peers, even if they are not mentioned by name, as local P2P markets are relatively small and limited to a specific region. In the case of closed order books combined with imposed security standards for the central entity, higher privacy protection can be guaranteed. However, the more data must be shared with the central entity, for example, on individual flexibility potential, the more privacy concerns arise.

### 4.3.3 | Regulatory framework

Using a central optimisation for allocation while considering network constraints in the optimisation algorithm in most of the cases requires system operators to clear the market by themselves as network data is not available for other actors. This raises concerns related to the German (and European) unbundling regulation as system operators are not allowed to participate in electricity trading. When implementing a separate FM instead, to comply with the unbundling regulation, adjustment of incentive regulation and the tariff structure is needed to allow system operators to include costs resulting from flexibility procurement into tariff calculation. In the same way, locational price signals as a coordinating element between electricity markets and the underlying grid require a restructuring of the current tariff structure to allow for differentiated network fees depending on the grid situation. Furthermore, German policy currently does not intend to split the electricity market into different bidding zones to guarantee the same market conditions and prices for all participants as defined in § 3a StromNZV. An exemption for local P2P markets would be necessary. Therefore, all design options considered in this paper come along with extensive regulatory adjustment requirements. These findings are also consistent with the descriptions in Ref. [46].

### 4.3.4 | Scalability

Computational complexity is comparatively low when implementing a continuous trading scheme or classic auction designs. However, the integrated consideration of network restrictions requires additional consensus mechanisms and comes with a significant computational burden. Especially the calculation of the price signals $C_{b,s}$ is computationally expensive, as their influence on the network load cannot be determined ex ante and requires an iterative procedure. For the optimisation problem CD, computation times lay within the magnitude of double-sided auctions, but they increase rapidly with the occurrence of non-linearities or additional constraints.

### 4.4 | Comprehensive design variant assessment

Table 4 consolidates the results of the quantitative and qualitative analysis for the four design variants for ANM derived in Section 3.2 that combined a P2P allocation method from Section 4.1. The combinations of P2P allocation and ANM mechanism were selected based on their prevalence in our meta-study. This allows a comprehensive comparison of the overall performance of the different market designs for P2P trading with ANM. For representation, we introduce a four-point Likert scale with ++ being the best score and -- being the poorest. The selected market designs differ in terms of the implemented allocation method, pricing scheme, and the mechanism to consider network constraints.

## 5 | DISCUSSION AND CRITICAL REVIEW

The concluding Table 4 draws a picture in which none of the evaluated variants is superior in all criteria. Even though there were minor deviations between the municipalities analysed concerning the equality criterion, the effects of different market designs are reproducible and conclusive for different market environments. However, the example of Loebitz also shows that not all municipalities have the conditions in place to benefit significantly from P2P trading independent from the chosen market design. In general, complexity and opacity significantly increase the more the P2P trading is influenced by the current grid situation. Whereas comparatively simple variants such as CO & ZN show good efficiency scores and good scalability, the lack of privacy protection due to the open order book can have a decisive impact on user acceptance. Downstream FMs such as UN & FM have been the subject of practical research projects for several years and therefore often meet the regulatory requirements better than other variants. However, due to the separated two-stage approach, they demonstrate significant limitations in terms of combined market efficiency. Besides, they face the inherent problem of strategic bidding behaviour, further explained in Ref. [8]. At the expense of added complexity, DC & PS can lead to improved market efficiency in terms of P2P revenue as well as the costs for congestion relief. Relying on a closed order book and reducing the amount of data that needs to be shared with the trading platform for flexibility deployment also enhance privacy protection. Therefore, especially the DC & PS market design achieves high scores for this KPI. From the user's point of view, central dispatch optimisation is the most complex and opaque approach. Besides, with a focus on European regulations, the direct involvement of the network operator in electricity trading is a critical aspect concerning the CD market design. Nonetheless, the method represents the optimum for many quantifiable criteria and can be adjusted to specific market purposes by adapting the objective functions as required.

**TABLE 4** Comprehensive KPI-assessment for four selected design variants

| | CO & ZN | UN & FM | DC & PS | CD |
|---|---|---|---|---|
| Simplicity | ++ | + | - | -- |
| Privacy protection | -- | + | ++ | - |
| Market efficiency (gross profit) | + | -- | ++ | ++ |
| Market efficiency (welfare) | -- | + | - | - |
| Equality | ++ | -- | - | + |
| Self-sufficiency | + | -- | ++ | ++ |
| Congestion relief efficiency | + | -- | + | ++ |
| Regulatory framework | - | + | + | -- |
| Scalability | ++ | + | -- | - |

Various sources might argue that the mechanisms presented here do not constitute full P2P markets, as their architecture is rather system-centric than peer-centric [12, 42]. According to this definition, genuine P2P markets would eliminate the need for an intermediary and rely exclusively on multi-bilateral negotiations. On the downside, this concept has very limited scalability and is hardly feasible in practice, as the number of connections is proportional to the number of connected peers squared, according to Metcalfe's law. Since the securing of the network restrictions is nevertheless the responsibility of a central system operator and thus nullifies any advantages concerning privacy protection, this variant was not considered in the analysis. However, there are numerous approaches to decentralised consensus optimisation (e.g. ADMM and RCI) that divide the solving of the central dispatch problem among a large number of peers [3, 53, 54]. As the original optimisation problem is unaltered in this case, the market performance should match the result of design variant CD. However, in terms of privacy protection and scalability, distributed optimisation approaches perform significantly better than their centralised counterparts. Peers do not have to disclose personal constraints with a central entity, and computing power can be outsourced to multiple processors.

### 5.1 | Methodological simplifications

In terms of the simulation environment, we adapted various simplifications such as the two-node network model or the ZI trading strategy from existing literature. Since they have already proven appropriate the studies cited, we do not assume that they have significantly distorted the results. This is also supported by the fact that the findings were reproduced in three different digital communities. However, it is important to note that in the current set-up ANM mechanisms only affect P2P transactions and not residual balancing trades. For holistic system analysis, export and retail transactions, including their impact on the grid, need to be considered. In this case, the chosen two-knot approach does not suffice. Thus, we strive to enhance the model by including real-world grid topologies and advanced bidding strategies. In addition, the market penetration of battery storage and electric vehicles is yet to be investigated. Especially within P2P markets, this group of flexible assets can leverage new liquidity potentials and make an essential contribution to the ANM.

## 6 | CONCLUSION AND OUTLOOK

LEMs not only generate revenue for local prosumers and consumers but can also contribute to a stable grid operation when combined with appropriate ANM mechanisms. In our paper, we described and categorised various contemporary LEM and FM market designs in a comprehensive meta-study. The main design variants emerging from that study were evaluated utilising an agent-based simulation environment and data from German sample communities focussing on their allocation efficiency and ability to provide ANM. Besides the evaluation of economic and technical KPIs, also user acceptance and practicability were discussed. For our sample communities, we found that revenue-optimising variants can gain up to a 35% gross profit increase over the conventional paradigm with retailers and regulated feed-in tariffs. Though, when the focus is shifted from communal earnings to individual welfare, auction mechanisms with uniform pricing are advantageous. Concerning their ability to relieve network congestion, we found integrated allocation mechanisms such as central dispatch optimisation to be the most efficient. Although the market designs analysed offer various advantages over the status quo, for all variants, we were able to identify significant regulatory challenges currently impeding implementation in Germany. While we cannot propose a one-fits-all solution, our analysis shows that integrated optimisation methods perform well when particularly efficient allocation mechanisms are required. Separate trading zones or downstream FMs have proven appropriate where market participants value simplicity and scalability. The computation of network-oriented price signals is often more intuitive than the CD allocation but requires long computation times due to the iterative methods and is thus hardly applicable to larger markets. Prospectively, we aim for the implementation of real-world grid topologies as well as advanced bidding strategies in our simulation environment. However, what we find every bit as important are concentrated efforts to integrate research designs into the existing energy market framework and consequently pursue practical living lab research.

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### CONFLICT OF INTEREST

No conflict of interest has been declared by the author(s).

### DATA AVAILABILITY STATEMENT

The data and scripts that support the findings of this study are available from the corresponding author upon request.

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# APPENDIX

**TABLE A1** Meta-study

| Project/Source | Concept | Allocation mechanism | Pricing rule | Time frame | ANM mechanism |
|---|---|---|---|---|---|
| DeTrade [18] | Electricity trading | Double auction-optimisation | Uniform marginal pricing | Intraday | Not included |
| Elecbay [19] | Electricity trading | Continuous trading | Discriminatory | Intraday | Validation and adjustment by network operator |
| Energy Collective [4] | Electricity trading | Multibilateral trading | Discriminatory | Close to real-time (≤15 min) | External price signal |
| Etiblogg [20] | Electricity trading | Continuous trading | Discriminatory | Close to real-time (≤15 min) | Not included |
| Guerrero et al. [21] | Electricity trading | Continuous trading | Discriminatory | Close to real-time (≤15 min) | Adjustment by DSO/TSO |
| Khorasany [22] | Electricity trading | Double auction-order book | Uniform (average mechanism) | Intraday | External price signal |
| Kim et al. [23] | Electricity trading | Double auction-order book | Discriminatory | tbd | Transaction zoning |
| LAMP [24] | Electricity trading | Double auction-order book | Uniform marginal pricing | Close to real-time (≤15 min) | Not included |
| Morstyn et al. [25] | Electricity trading | Multibilateral trading | Discriminatory | Day-ahead + Intraday | External price signal |
| Pebbles [26] | Electricity trading | Double auction-optimisation | Uniform marginal pricing | Day-ahead | tbd |
| Quartierstrom 1.0 [27] | Electricity trading | Double auction-order book | Discriminatory (mean value) | Close to real-time (≤15 min) | Considered before the LEM matching |
| RegHEE [28] | Electricity trading | Double auction-order book | tbd | Close to real-time (≤15 min) | tbd |
| Hoof Dalem 2.0/USEF [29] | Electricity and flexibility trading | P2P: Double auction-order book<br>FM: One-sided auction-optimisation | Considered in the matching algorithm | Day-ahead | Considered in the matching algorithm |
| TUMCreate market [30] | Considered in the matching algorithm | P2P: Multibilateral trading<br>FM: One-sided auction-optimisation | Uniform marginal pricing | Close to real-time (≤15 min) | External price signal |
| Zhang et al. [31] | Electricity and flexibility trading | One-sided auction-optimisation | P2P: discriminatory FM: uniform | Day-ahead | Considered in the matching algorithm |
| Zhou et al. [32] | Uniform marginal pricing | P2P: Continuous trading<br>FM: uniform | P2P: discriminatory (mean value)<br>FM: uniform (ask) | Day-ahead | Considered in the matching algorithm |
| ALF [33] | Electricity and flexibility trading | One-sided auction-optimisation | Discriminatory | Future + day-ahead | Consideration before matching |
| Cornwall LEM [34] | Electricity and flexibility trading | P2P: continuous trading FM: tbd | Uniform marginal pricing | Future + Intraday | Considered in the matching algorithm |
| Flex-DLM [35] | Flexibility trading | One-sided auction-optimisation | Uniform marginal pricing | Day-ahead + Intraday | Considered in the matching algorithm |
| Flex2Market [36] | Flexibility trading | Double auction -order book | Discriminatory | Intraday | Transaction zoning |
| Morstyn et al. [37] | Flexibility trading | Multibilateral trading | Discriminatory | Day-ahead | Considered in the matching algorithm |
| ReFlex [38] | Flexibility trading | One-sided auction-optimisation | Discriminatory | Day-ahead | Considered in the matching algorithm |