Comparison of Pricing Mechanisms in Peer-to-Peer Energy Communities

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Abstract:

Digitization enables new participation concepts to be designed, especially for the lower voltage levels, small-scale producers and consumers. Building on extensive regionalized data, German municipalities can be simulated in a newly developed simulation framework. The framework generates all necessary agents for a given municipality on demand and allows the simulation of multiple energy economic use cases. One popular use case is P2P energy sharing. P2P energy sharing communities are a means of integrating small-scale producers, consumers and flexibility options into the energy system. These communities are either in a local geographical area or driven by consumers and producers with mutual goals. Three different pricing mechanisms, i.e., supply and demand ratio (SDR), mid-market rate (MMR) and bill sharing (BS) are introduced and compared for different municipalities. The advantages and disadvantages are shown for all mechanisms using example communities. It becomes apparent that different mechanisms are better depending on the prevailing site conditions.

Keywords: p2p energy communities, simulation, pricing mechanisms, flexibility

1 P2P Energy Communities

Digitalization creates new opportunities for integrating small-scale renewable energies and flexible consumers into the energy system [1]. A key question is how to ensure that these distributed energy resources continue to operate economically after the expiration of subsidies for renewable energies. One possible solution, enabled by digitization, are so-called peer-to-peer (P2P) energy communities. Pricing mechanisms play an essential role in determining the peers' economic benefits and attracting potential customers to participate in P2P energy sharing communities. Pricing mechanisms consider multiple factors, such as energy generation and consumption within the community, exchange electricity prices as well as prices for purchasing from the utility grid. The following research questions are answered in this paper:

- What are P2P energy communities, and how are they defined?
- What are possible pricing mechanisms?
- How can P2P energy communities be simulated?
- How do prices differ depending on local site conditions?

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Based on a comprehensive literature review, the existing definitions of P2P energy communities are compared, and relevant description criteria are derived in section 2. A Python framework is developed and introduced in section 4 to simulate and methodically compare pricing mechanisms in P2P energy communities at the municipality level. For this purpose, relevant input data like individual household load profiles, generation from renewable energy sources (RES) and other datasets are processed using statistical methods and used as input for pricing mechanisms. In addition, pricing mechanisms described in the literature are collected and described in section 5. A comparison for different municipalities is shown and interpreted in section 6.

2 Relevant Definitions

Recently, extensive research has been carried out on peer-to-peer (P2P) energy sharing. This section is dedicated to providing an overview of existing definitions regarding the concepts and terminology, and to introduce a novel definition on how we understand the P2P energy sharing concept.

P2P energy sharing has previously been defined as a platform that allows prosumers to "trade their energy within a connected community", thus determining the price, amount and counterparty individually as a prosumer [2]. Another approach included the maximization of the prosumers benefit by trading or sharing energy among each other [3]. [4] combines both aspects and defines the term as prosumers trading excess energy from distributed energy resources (DER) directly without intermediary involvement, while aiming to maximize their economic benefits and maintaining full control over their DER. The same authors introduce a broader interpretation of the term where a third party, e.g., an aggregator or a coordinator, may be involved in the process depending on the corresponding market design. Furthermore, [5] strongly integrated the community aspect by defining P2P energy sharing as an approach allowing residential prosumers to share the local DER based on a long-term arrangement and a pre-agreed cost-sharing mechanism. Based on the literature review, we find that the term P2P energy trading is frequently used in the same context. For instance, [6] define P2P energy trading as "the direct energy trading among local consumers and prosumers". The term is also used in a larger scale context by [7] and [8] who state that P2P trading can not only occur between individual peers but also trading groups, e.g., communities. Both terms are strongly interrelated since they are sometimes used interchangeably in the literature and their definitions show considerable similarities. In the following, we introduce a novel definition of P2P energy sharing considering a clear distinction to P2P energy trading.

In this study, P2P energy sharing is defined as peers sharing their surplus energy with other energy customers to improve economic, environmental benefits and add technical, institutional values to the entire community. A peer in this context refers to one or a group of energy customers (end-users) who can be pure energy consumers, prosumers, or flexumers [9]. The term "peers" hence specifically refers to the energy customers in the same hierarchy of the energy system. For instance, the "full P2P market" structure proposed in the work of Sousa et al. should be excluded [10]. The economic benefit is not the only incentive for prosumers to participate in P2P energy sharing communities. Peers who are willing to engage in P2P energy sharing are, to some extent, "collectivist." They pay more attention to the whole community's benefits than the individual's. Their objectives are diversified, e.g., strong preference for clean energy with known origins, minimizing the community's electricity costs, reducing the CO_2 emissions in the community, reducing peak loads, increasing network efficiency, improving system reliability, and decreasing the dependency on imported energy. On the contrary, peers in P2P energy trading are self-interested and finance oriented. In this case, peer's ultimate objective is to maximize individual economic benefits. More attractive P2P electricity prices stimulate prosumers to sell their surplus energy to other peers rather than the retail market (i.e., injecting surplus energy into the utility grid). Therefore, P2P energy trading usually occurs between peers who are geographically close to avoid unnecessary transmission costs. The relationship between P2P energy sharing and trading is illustrated in Figure 1. Since the former has a broader definition, it includes the latter.

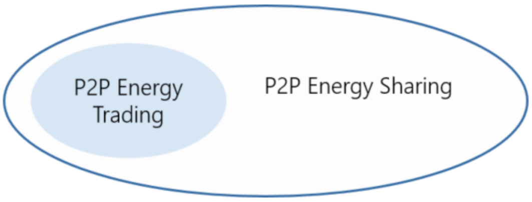

Figure 1: Illustration of the relationship between the definitions of P2P energy sharing and P2P energy trading

Furthermore, this study also presents two conceptually possible ways to form a P2P energy sharing community. A P2P energy sharing community can be built by consumers (demand) and producers (supply) in the same local geographical area, like a neighborhood, a village, or a municipality. This kind of community is commonly regional and small-scaled. Also, being geographically close can reduce energy loss during transmission and avoid unnecessary grid fees (if corresponding regulations permit this). A weakness is that the distributed generator's power generation profiles may have high similarity due to similar weather conditions. Consequently, the excess energy cannot be used most efficiently if this community has a high penetration of a specific DER (e.g., PV), limited energy storage capacity or only few flexibility options. However, the resulting low prices may incentivize the procurement of additional storage or flexibility options.

The other way to build a P2P energy sharing community is that a group of peers form a community voluntarily driven by mutual goals. These goals can be various, such as maximizing the community's welfare, reducing CO_2 emission or reducing peak loads. In this case, peers within a community might reside in geographically dispersed locations. Energy sharing is nationwide and can be realized by transferring electricity through the utility grid. Notice that multiple objectives may be incompatible, i.e., one goal may be reached by sacrificing the other goal. Hence, P2P energy sharing communities can be constructed separately based on a variety of objectives. Energy customers who share a mutual goal gather and form a community.

Since most energy sharing activities are supposed to be monetary-involved, economic benefits for individuals or the entire community play an unneglectable role. Therefore, market designs are essential to define stakeholders, the responsibilities of stakeholders, operating and pricing mechanisms in P2P energy sharing communities. Zhou et al. classified the existing market designs into three groups based on the centralization level: centralized, distributed, and decentralized [11].

In a centralized market design, the coordinator plays a similar role as energy aggregators of a virtual power plant. The coordinator is responsible for collecting energy-related information such as power consumption and generation profiles of peers and managing the prosumers' flexible electrical devices. The internal energy price (P2P price) is then defined by the predetermined pricing mechanism and collected information. The mutual goal (optimum) of a community can be achieved in this market design. Nevertheless, the optimum for the community must not always be optimal for each peer. That might discourage peers from participating in P2P energy sharing. Another concern is privacy exposure since peers need to provide much more information in a centralized market than in a distributed or decentralized market.

In a fully decentralized market design, each peer can directly trade and set up bilateral contracts with others based on its objective or preference. The high autonomy of participants is one of the typical characteristics of a decentralized market. The drawback is that the trading outcome under a decentralized market design is full of uncertainty. On the one hand, the peers' decision-making process (i.e., schedule energy consumption and generation, bidding) is independent, complex, and unpredictable in reality. On the other hand, a trading order between peers may fail to settle due to network constraints, e.g., voltage excursion, thermal overloading [12]. The Blockchain-technology is a much discussed enabler for fully decentralized market designs (see [13], [14], [15], [16], [17], [18])

A distributed market combines the advantages of centralized and decentralized markets. Peers own a higher autonomy than in a centralized markets and can fully control their devices. Peers send their bids to the coordinator individually (the intention to buy or sell energy in a certain amount at a specific price). The P2P prices are provided by the coordinator based on the collected bids and the predefined pricing mechanism. In a distributed market, the coordinator only assists the bidding process and calculates the P2P prices without taking control of the flexible electric devices.

In the following paper we compare different pricing mechanisms for exemplary municipalities in Germany, based on a newly developed simulation framework.

3 Methodology

We develop a simulation framework on the municipality level to evaluate potential P2P-pricing mechanisms for different regions in Germany. Figure 2 describes the methodology applied in this work.

The simulation framework includes relevant data such as electric and thermal household loads, residential storages and and electric vehicles including their associated load profiles. Additionally, generation profiles are included for renewable energy resources in the area. Based on this framework, multiple use cases can be evaluated in the future. In this work, we introduce different P2P-pricing mechanisms and compare them for different municipalities. The simulation framework is introduced in detail in the following section.

4 Simulation Framework

The following section provides an introduction of the preprocessing module, a part of a Python-based software framework used for simulations and analysis of arbitrary energy related use cases on building level inside a municipality. The framework is currently being developed at the FfE within the projects InDEED and PEAK[2]. The software framework is divided into the preprocessing module and several independent use case modules. While the preprocessing module is used to prepare all necessary data, the use case modules contain the source code for simulating and analyzing the research questions related to the respective use case. This section serves as an overview of the data sources and methodologies utilized by the preprocessing module.

Among others, the preprocessing module includes geodata and temporal data on consumption and generation for individual buildings and power plants. It is used to gather and arrange the necessary data of a municipality of interest and provide the information as Python-objects, which are then used to perform the actual simulation task. The preprocessing module is connected to the database of the FfE regionalized energy system modelling tool (FREM) [19], containing various relevant datasets like census data on population and buildings or administrative geodata. For this study, the preprocessing module was used to provide the relevant data (e.g., buildings, residential PV systems and storages) of the municipalities of interest. Thus, spatially the model considers the level of individual buildings or power plants. In addition to "status quo" analysis, the preprocessing module also facilitates the study of different scenarios by allowing altered technology penetrations for residential storages and PV systems as well as BEV's.

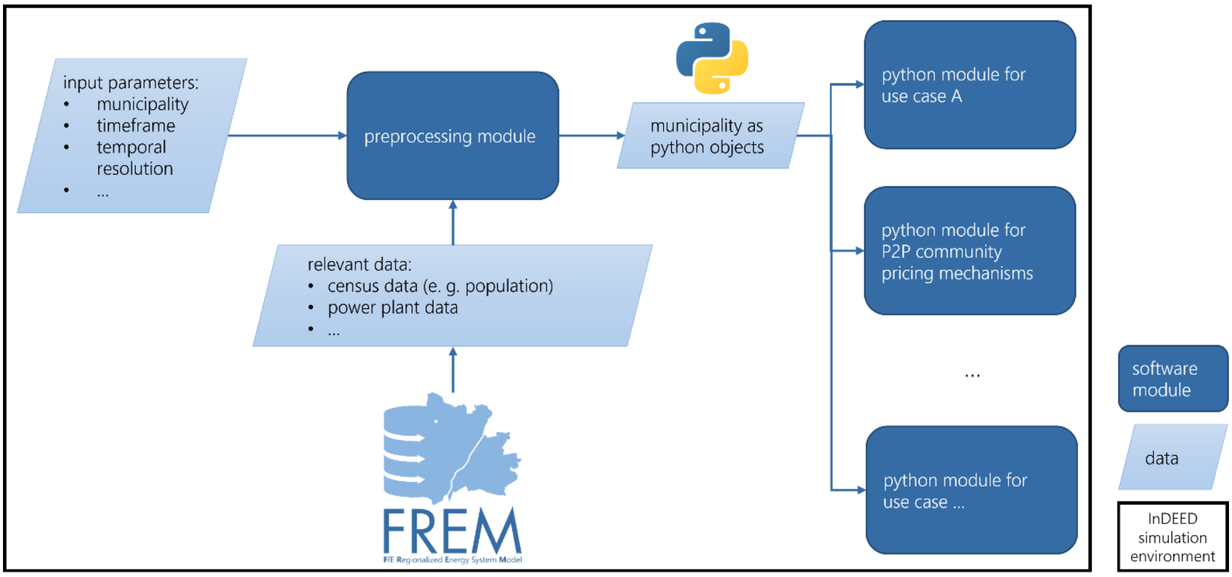

Figure 2: General overview of the InDEED simulation framework

[2] The projects "PEAK – Integrierte Plattform für Peer-to-Peer Energiehandel und Aktive Netzführung" (www.ffe.de/peak) and InDEED (www.ffe.de/indeed) are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) - funding code PEAK: 03EI0635F, InDEED: 03E16026A

4.1 Input parameters

The preprocessing module takes an identifier corresponding to the municipality of interest. All spatial data is filtered accordingly to assets located within the area of this administrative unit. Furthermore, three temporal parameters need to be provided, defining the time frame of the simulation (i.e., start time, end time and temporal resolution). These parameters are used to subset all temporal data (e.g., load profiles) to match the time frame. The temporal resolution can be accurate up to one minute.

4.2 Buildings and Households

The data source for modelling buildings and households is the German census dataset, i.e., the grid-based results of the census (from here on census grid; [20], [21]), which features a higher spatial resolution (100 m x 100 m) as opposed to census data based on administrative units. The census grid contains features per hectare including the following:

- number of residential buildings by building type
- number of residential buildings by building age
- number of households by household size

Thus, the dataset facilitates a more accurate mapping of the settlement structure. The use of these characteristics is due to the fact that they are decisive in the modelling of electrical and thermal loads. The manifestations of those features are listed in Table 1.

Through nondisclosure measures applied to the census grid that slightly alter the original data, the features listed above are not guaranteed to be consistent for each cell (e.g., number of buildings by type may derive from the number of buildings by age). Furthermore, those features do not allow to directly extract buildings featuring both attributes (age and type). Thus, in order to deduce the building stock where type as well as age is known for each individual building, heuristics are applied involving the distribution of those features for all buildings inside the area of interest (i.e., census data for administrative units [22]), so that the modelled building stock matches the settlement characteristics of the respective municipality. Households are allocated to individual buildings per cell iteratively by (1) determining the building type of household and then (2) randomly assigning it to a building of this type. Step (1) is done by weighted sampling the building type from the distribution of population by building type for the area of interest [22].

4.3 Renewable generators

For all plant types except hydropower plants (master data according to [23]), the current inventory (resembling the state of 2019) is extracted from the core energy market data register (Marktstammdatenregister; MaStR) maintained by the German Federal Network Agency [24]. In addition to the geolocation of the generators, their installed power and the year of commission are included. Data of onshore wind power plants are supplemented using data provided by the transmission system operators [25]. Photovoltaic systems (PV systems) are categorized into the sectors "residential", "tertiary" and "agricultural" in an upstream process according to [26]. In the preprocessing module only PV systems of the residential sector may be assigned to buildings, i.e., modelled as residential PV systems. Master data of PV systems are enhanced with features describing the alignment angle that enable a more precise synthesis of generation profiles [19]. These values are determined by weighted sampling from available MaStR data.

Table 1: List of features and manifestations for buildings and households

Feature	**Manifestation**
Building type	One-family house Two-family house
	Apartment buildings (3 - 6 apartments)
	Apartment buildings (> 6 apartments)
Building age	Before 1980
	1980 – 2000
	2001 and later
Household size	1-person-household
	2-person-household
	3-person-household
	4-person-household
	5+-person-household

Generation profiles of power plants are based on various sources depending on the energy carrier. In all cases, profiles are transformed (if necessary) into a pseudo-minute accuracy and then again aggregated into the desired temporal resolution defined by the input parameters (see section 4.1). The PV generation profiles are calculated in advance based on radiation data of the year 2019 with a spatial resolution of 0.2° (around 22 km by 15 km; [27]). Due to limited access to this data set, one profile is calculated per district and thus, PV systems in municipalities of the same district are modelled using the same profile. PV generation profiles are scaled by a factor of 0.91 to account for the efficiency of the inverter. As for roof-mounted PV systems a factor of 0.965 is applied additionally due to missing airflow cooling. Generation profiles regionalized at district level are used for modelling the load of wind power plants. Therefore, districts have been classified by wind frequency (based on weather data from 2011 to 2013) and allocated a reference load profile that has been derived from weather data of 2019 using a characteristic curve of a typical wind power plant usually installed in locations with these conditions [28], [29], [30]. The generation profiles of biomass and hydropower plants are synthesized according to [31]. Profiles for generation based on biomass is available at district level. However, profiles for hydropower generation are not regionally different. The regionalization of generation profiles ensures that locally different conditions are incorporated into the modelling of biomass, wind and PV power plants.

4.4 Residential PV systems

Allocation of residential PV systems is done by first intersecting their geolocation with the cells of the census grid and then assigning them to buildings related to same cell. The latter is performed iteratively per cell by weighted sampling by building type, where one- and two-family houses have three times the chance to be selected as opposed to apartment buildings [32], [33]. The penetration of residential PV systems can also be set manually. Only one- and two-family houses will be equipped with a PV system in this case. The master data of the PV systems are synthesized based on the data from the register of master data by randomly determining the installed capacity weighted by frequency and choosing the alignment parameters using the procedure described above.

4.5 Residential storages

The inventory of residential battery storages is taken from the MaStR. Storages are filtered by voltage level only and have a maximum capacity of 10 kWh. The frequency distribution of the capacity of battery storages in Germany supports this threshold since the significant majority is below 11 kWh [34]. Because most datasets are missing a geolocation, storages are referenced to buildings that have previously been assigned a PV system. Allocation is done iteratively by calculating the ratio r between storage capacity and installed PV power for all possible building candidates and subsequent weighted sampling based on the distribution of r based on [34]. Lastly, the building is chosen where r is nearest to the sampled value. Regarding charging and discharging, an efficiency of 94 % is assumed. As with residential PV systems, it is possible to manually determine the penetration of residential storages. Considering that only buildings with a PV system may be equipped with a storage, the residential storages are synthesized based on data for randomly sampled PV systems, that are already modelled. The capacity is derived from the power of the PV system by sampling a value for r from [34] while charging power depends on the ratio of charging power and capacity c. The value for c is again sampled from [34].

4.6 Electric and thermal load of buildings

Many modelling and simulation tasks in the energy sector rely on standard load profiles (SLP). These profiles are easy to implement since the dynamics over time are already known and must only be scaled to meet the total load. Thus, the downside of SLPs is, that individual load peaks are neglected. To account for this, the consumption of electric and thermal energy per building have been synthesized based on an agent-based model by [35] which generates distinct load profiles based on the activity of independent agents. In total, data for around 6,000 buildings with 40,000 households that is used within the preprocessing module have been pre-calculated using this model containing information about the number of persons per household, building type as well as building age and a building specific customer value used for calculation of the room heating demand. By utilizing these features fitting electric and thermal (warm water) load profiles are chosen for each household which are in turn aggregated at building level. The room heating is also calculated at building level using an SLP in combination with regionalized (district level) daily mean temperatures of the year 2019 and the building specific customer value [29], [36], [37].

4.7 Battery electric vehicles and mobility profiles

In addition to electric and thermal load profiles, the agent-based model by [35] also includes battery electric vehicles (BEV) by size (small, medium, large) and mobility profiles per household. Every household with more than one person capable of driving is equipped with two and otherwise one BEV. Based on the activity of the agents, mobility profiles have been generated containing the time of departure and arrival, distance, energy consumption as well as the average speed per trip with a 15-minute accuracy. The battery capacity of BEV's is estimated according to its size and the charging power is constant. Furthermore, it is assumed that BEV's are charged with full power immediately after arrival at home until the vehicle's battery is fully charged or another trip is made. The loading profiles of BEV are then calculated based on these assumptions. In order to resemble the current stock, the number of BEV's for 2019 on district level is disaggregated based on population data on municipality level [38], [39]. Since by default all buildings are assigned at least one BEV, redundant BEV's are discarded randomly, so that the target value is reached. During this step, BEV's allocated in buildings not equipped with a PV system are selected preferably. It is also possible to manually set the penetration of BEV's. In this case only the predefined proportion of BEV will be considered.

4.8 Additional data

Due to the relevance in many energy-economic applications, time series data on greenhouse gas emissions and electricity exchange prices are provided. The former is based on historical generation data from ENTSO-E [40] and specific emission factors by energy source [41]. These data are transformed into hourly greenhouse gas emissions according to [42]. The average 15-minute intraday price of all transactions of EPEX of continuous trading in Germany and Austria [43] is used as an external price signal. In correspondence to the profiles, both greenhouse gas emissions and electricity exchange prices are used for the year 2019.

5 Pricing mechanisms

Several different pricing mechanisms have been proposed in existing studies to determine P2P prices. This paper discusses and analyzes three pricing mechanisms, i.e., supply and demand ratio (SDR), mid-market rate pricing (MMR), and bill sharing (BS). Under these mechanisms, P2P prices are calculated based on predefined mathematical formulations. That makes the whole pricing process more straightforward, time-efficient, and understandable to customers than other mechanisms such as bilateral contract-based mechanism, double auction models, and discriminate pricing techniques using game theory [12]. Although peers do not directly participate in price negotiation or price setting in the SDR, MMR, and BS mechanisms, they can influence the P2P prices by changing individual energy demand or supply. The following section introduces the mathematical formulation and the evaluation of SDR, MMR, BS pricing mechanisms, based on the price components in Figure 3.

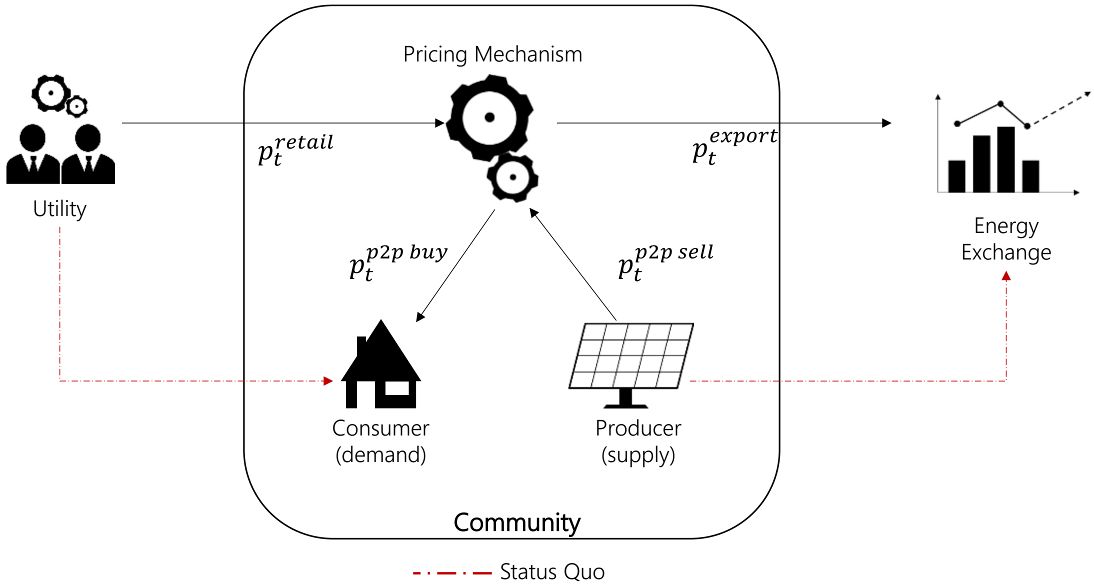

Figure 3: Illustration of price components of P2P energy sharing communities

5.1 Supply and Demand Ratio (SDR)

Liu et al. proposed the SDR pricing mechanism based on the fundamental principle of economics, i.e., "the relation between price and SDR is inverse-proportional" [44]. Hence, product price will decrease when oversupply occurs on the market, i.e., the SDR ratio is larger than one. On the contrary, product prices will rise when demand is higher than supply, i.e., the SDR ratio is smaller than one. This principle can be applied to the energy market as well.

The energy supply of an individual peer refers explicitly to how much energy is surplus after self-consumption since self-generated energy is always used preferentially. Similarly, the energy demand of an individual peer presents how much energy is still needed to satisfy the demand after self-consumption. Thus, the SDR ratio at a specific time can be calculated as the ratio of the total energy supply and the total energy demand of peers in the P2P energy sharing community.

The P2P prices under the SDR mechanism can be calculated using the following mathematical formulation from [44].

$$p_t^{p2p\ sell} = f(SDR) = \begin{cases} \dfrac{p_t^{export} \cdot p_t^{retail}}{(p_t^{retail} - p_t^{export}) \cdot SDR_t + p_t^{export}} & 0 \leq SDR_t \leq 1 \\ p_t^{export} & SDR_t > 1 \end{cases} \quad (1)$$

$$p_t^{p2p\ buy} = \begin{cases} p_t^{p2p\ sell} \cdot SDR_t + p_t^{retail} \cdot (1 - SDR_t) & 0 \leq SDR_t \leq 1 \\ p_t^{export} & SDR_t > 1 \end{cases} \quad (2)$$

The retail price and export price in Equations (1) and (2) refer to the price of purchasing deficit energy from the utility grid and selling surplus energy to the grid, respectively.

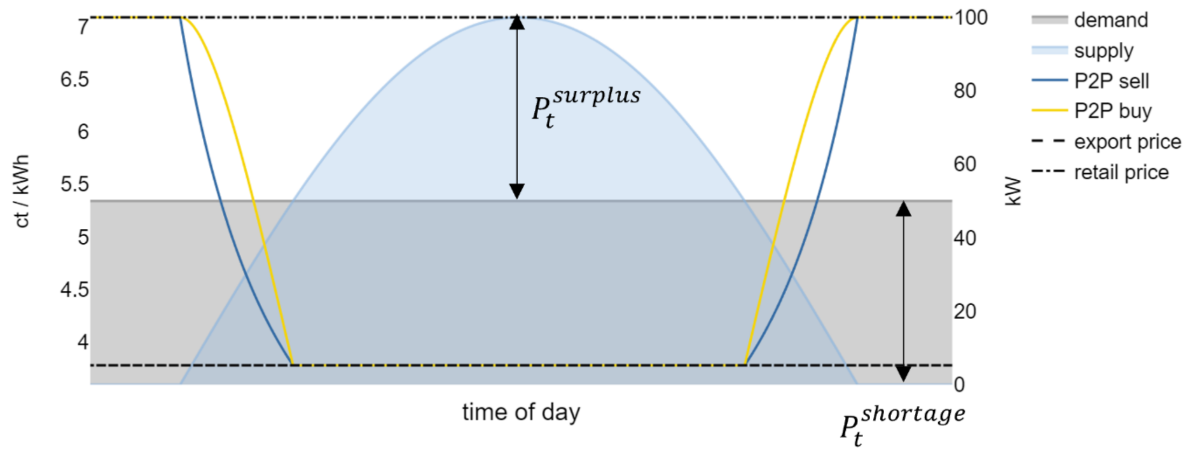

Figure 4: Illustration of P2P prices under the SDR mechanism

Figure 4 illustrates the P2P prices of the SDR mechanism for a single day with synthetic data for illustrative purposes. The energy supply is modeled based on a typical generation profile of PV systems (the peak is reached at noon and no supply is available at night-time). The demand is assumed to be constant. Besides, export and retail prices are constant for simplification purposes while the export price is always below the retail price.

The P2P prices of the SDR mechanism lie between the export price and the retail price. The upper bound of P2P prices is the retail price. When no energy supply is available, i.e., the SDR ratio is equal to zero, energy demand can only be fulfilled by purchasing energy from the grid at the retail price. Thus, the P2P buying and selling prices are both the same as the retail price.

In contrast, P2P prices drop to the lowest level (export price) when energy oversupply occurs. Oversupply implies that surplus energy has to be fed into the grid and sold for the export price. When energy demand is higher than supply, the P2P selling price decreases with the increasing energy supply and increases when energy supply drops. However, P2P selling prices are always lower than or equal to P2P buying prices based on the given synthetic data.

Prices with zero supply are euqual to the retail price. These prices are a valuable incentive for additional supply, but do nothing for existing plants because they cannot take advantage of this price due to lack of flexibility and thus lack of generation. Therefore, the weighted average of the actually called prices is also presented in section 6.

5.2 Mid-Market Rate Pricing (MMR)

In the MMR pricing mechanism, the P2P price is set in the middle of the electricity price purchased from (retail price) and sold to the grid (export price) when the energy supply and demand within the community are balanced [45]. Once the energy supply and demand are mismatched, the additional costs or revenues of trading energy with the utility grid need to be considered in the pricing process. The mathematical formulation and clarification are as follows.

$$p_t^{p2p\,buy} = p_t^{P2P\,sell} = p_t^{mid} = \frac{p_t^{retail} + p_t^{export}}{2} \qquad (3)$$

$$\begin{cases} p_t^{p2p\,sell} = p_t^{mid} \\ p_t^{p2p\,buy} = \dfrac{p_t^{mid} \cdot \sum_{i=1}^{peers} P_t^{supply} + P_t^{shortage} \cdot p_t^{retail}}{\sum_{i=1}^{peers} P_t^{demand}} \end{cases} \quad (4)$$

$$\begin{cases} p_t^{p2p\,sell} = \dfrac{p_t^{mid} \cdot \sum_{i=1}^{peers} P_t^{demand} + P_t^{surplus} \cdot p_t^{export}}{\sum_{i=1}^{peers} P_t^{supply}} \\ p_t^{p2p\,buy} = p_t^{mid} \end{cases} \quad (5)$$

Equations (3), (4) and (5) present the P2P prices under the MMR mechanism scenarios of demand equal to supply, demand higher than supply, and demand lower than supply, respectively. Energy shortage and surplus of the entire community present the energy balance after P2P energy sharing.

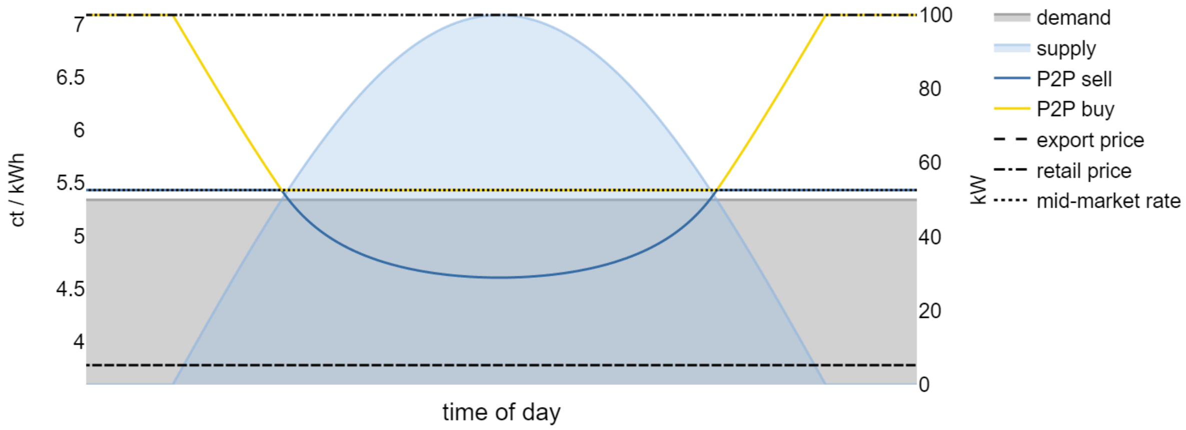

Figure 5: Illustration of P2P prices under the MMR mechanism

Figure 5 depicts the P2P prices under the MMR mechanism using the same synthetic energy demand and supply data as Figure 4. The P2P prices are always within the range of the export price and the retail price. In times of undersupply, e.g., during night-time, the P2P selling price is equal to p_t^{mid} while the P2P buying price settles between the mid-market rate (p_t^{mid}) and the retail price (p_t^{retail}). Depending on the quantity of undersupply, the P2P buying price is closer to p_t^{mid} (minor undersupply) or the retail price (major undersupply), so the cost of power bought from the grid is covered accordingly. During the time of oversupply at noontime, the P2P buying price is equal to the mid-market rate, while the P2P selling price settles between the mid-market rate and the export price obtained by selling the excess power to the market, depending on the magnitude of oversupply. Thus, major oversupply leads to a P2P selling price near the export price and minor oversupply results in P2P selling prices closer to the mid-market rate.

5.3 Bill Sharing Mechanism (BS)

Compared to the previous two mechanisms, the BS mechanism is more straightforward. Bill sharing is a cost-sharing method in which all peers in the community share the electricity cost and revenue equally throughout a predefined timeframe [3]. That results in a constant P2P selling and buying price. However, the P2P prices can only be calculated at the end of the billing period since the total cost and revenue can only be determined ex post.

$$p_t^{p2p\ buy} = \frac{p_t^{retail} \cdot \sum_{t=1}^{T} P_t^{shortage}}{\sum_{i=1}^{peers} \sum_{t=1}^{T} P_{i,t}^{demand}} \tag{6}$$

$$p_t^{p2p\ sell} = \frac{p_t^{export} \cdot \sum_{t=1}^{T} P_t^{surplus}}{\sum_{i=1}^{peers} \sum_{t=1}^{T} P_{i,t}^{supply}} \tag{7}$$

The notation in the BS mechanism is consistent with the notation in the MMR mechanism. The numerator of Equation (6) presents the total cost of purchasing energy from the grid to cover the energy shortage of the community throughout the simulation horizon. The denominator of Equation (6) is the aggregated energy demand of individual peers. The energy amount bought from the grid is always smaller than or equal to the aggregated energy demand.

Similarly, the P2P selling price is calculated as the total revenue of selling the community's surplus energy to the grid divided by the aggregated energy supply in the simulation period. The energy amount sold to the grid is always smaller than or equal to the aggregated individuals' energy surplus. Unlike the SDR and MMR mechanisms, P2P prices determined by the BS mechanism are calculated at the end of the billing period and constant throughout this period.

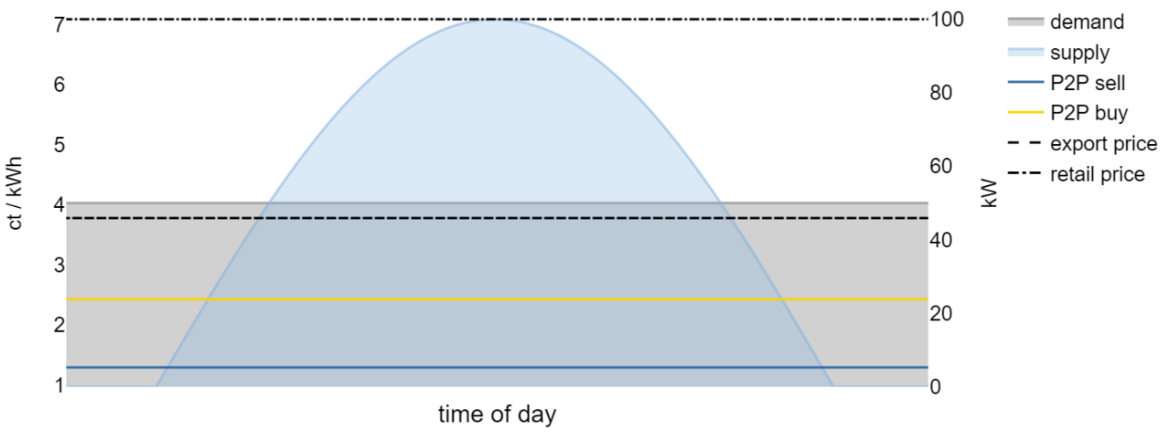

Figure 6: Illustration of P2P prices under the BS mechanism

Figure 6 depicts the P2P prices under the BS mechanism using the same synthetic energy demand and supply data as Figure 4 and Figure 5. As shown in Figure 6, P2P prices are not influenced by the energy supply and demand change. P2P selling price is lower than the export price since the revenue generation time (oversupply) is not throughout the day, and the revenue has to be shared evenly with each supplier. The P2P buying price lies between the export price and the retail price.

6 Results

To compare the effects of different pricing mechanisms depending on the varying structure of P2P energy sharing communities, we utilized the simulation framework introduced in section 4. For the purpose of demonstration, five distinct German municipalities are selected and evaluated concerning pricing differences. The characteristics of the communities as generated with the simulation framework are listed in Table 2. Note that inhabitants and the installed PV power may be underestimated due to reasons addressed below in the discussion in section 7. The data generated by the preprocessing module of the simulation framework has been used to calculate the demand and supply (after self-consumption) of these communities for the extent of one year using a temporal resolution of one hour. Since the relationship between demand and supply within each community is the key factor for pricing, the amount of time with over-/undersupply as well as the magnitude of over-/undersupply for all communities except Nieheim are displayed in Figure 7 (a). In order to avoid distorting effects due to the extremely high gap between the supply and demand side in Nieheim, the supply and demand ratio is displayed independently in Figure 7 (b).

Table 2: Key facts of the communities selected for the case study

ID	Name	Inhabitants	Installed power of RES in MW				Degree of Autarky	Self-consumption rate
			PV	Wind	Biomass	Hydro		
2554	Nieheim	4,366	4.8	35.8	2.9	0.0	100.0 %	3.3 %
2579	Minden	58,520	9.0	5.3	2.0	0.0	54.4 %	96.1 %
2919	Hofgeismar	11,387	2.8	0.0	2.2	0.0	83.7 %	75.6 %
4993	Henschtal	228	0.1	0.0	0.0	0.0	26.0 %	67.4 %
5429	Gerlingen	16,073	1.6	0.0	0.0	0.0	6.8 %	100.0 %

The municipality Nieheim is characterized by very high installed capacity of RES (especially wind power) resulting in constant oversupply throughout the year.

Due to high demand (around 18k inhabitants) and low capacity of RES, the town of Gerlingen has always less supply than demand and a maximum SDR of 0.5. Since the generation side is served exclusively by PV systems, the amount of power generated within the community is zero around half of the time.

With similar demand as Gerlingen, but more PV capacity and some capacity in biomass and hydro power generation, the town of Hofgeismar shows oversupply at around 60 % of the time. Due to the lower but constant generation provided by biomass and hydro power plants, the SDR never reaches zero.

Regarding population, Minden is the largest of the municipalities selected for this case study. The resulting high demand can only be covered from within the community at around 15 % of the time while the remaining time of the year is characterized by undersupply.

Henschtal is distinguished by a small population and PV as the only RES. The situation is dominated by undersupply since the demand can only be covered from local sources around 17 % of the time. Due to the lack of constant generators, SDR is equal to zero around half of the time (night-time).

Due to the differences of supply and demand, resulting prices within the municipalities differ heavily, as can be seen for the selected P2P-community pricing mechanisms SRD, MMR and BS as described in the following sections. The p_t^{export} was set equal to the stock price and the p_t^{retail} was set at 7.09 ct/kWh equaling the share of energy costs, procurement and sales in Germany 2019 [46]. This assumption presumes that the current cost surcharges on the energy price by the utility are completely eliminated in favor of the P2P community. In practice, however, the energy supplier will not be completely eliminated. The addition of constant or variable surcharges on the energy price, e.g., by the community operator, or the introduction of a flat rate model are realistic additional costs, which are, however, neglected in the following.

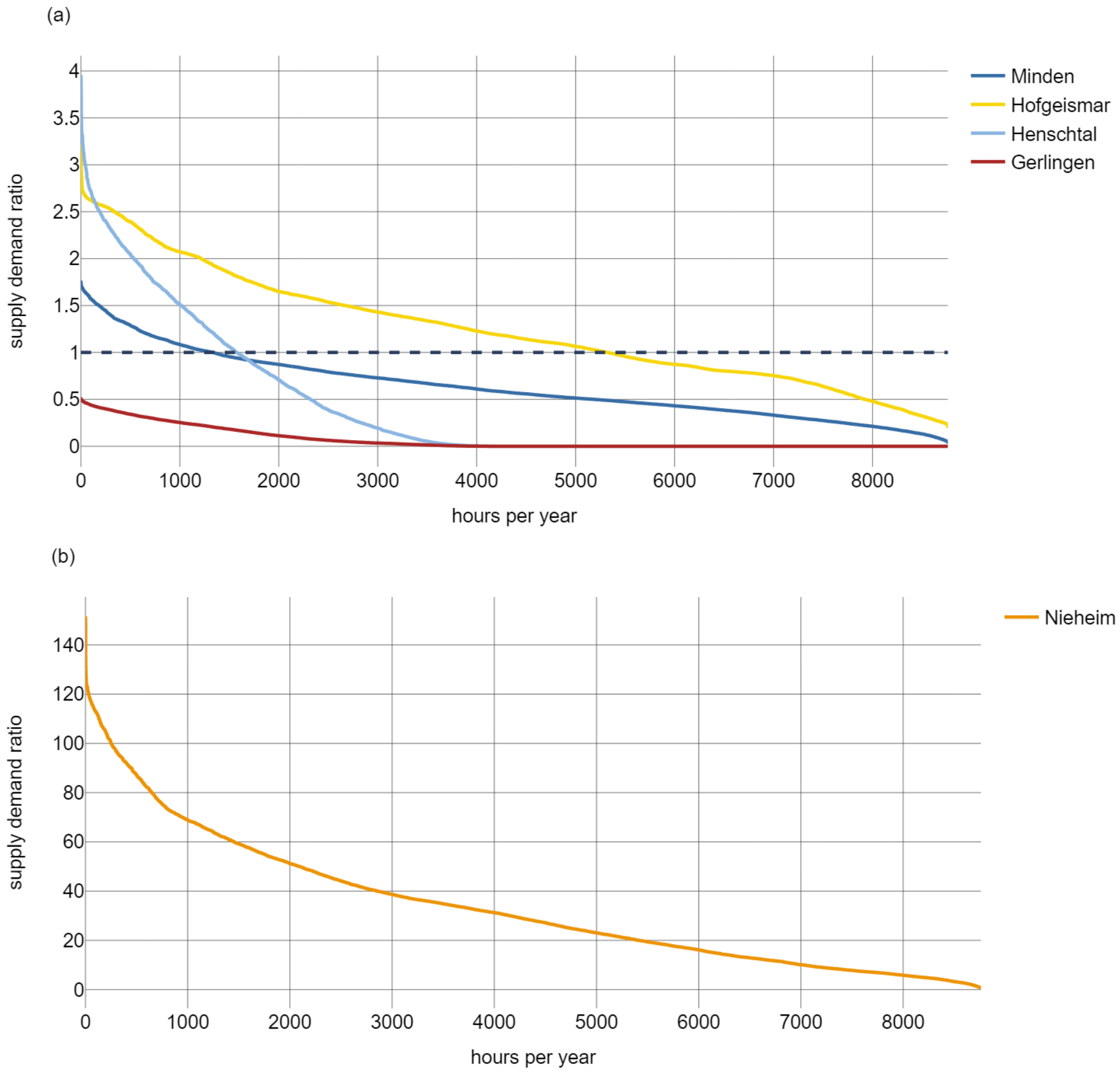

Figure 7: Annual duration line of the supply and demand ratio of the municipalities Minden, Hofgeismar, Henschtal, Gerlingen (a) and Nieheim (b).

Note, that in Figure 8, Figure 9 and Figure 10 in the following sections, the resulting prices have been clipped to the 1st and the 99th quantile in order to remove extreme outliers and avoid distorted illustrations. Thus, the statistical values illustrated by the box plots refer to the trimmed data set. The data points not included in these figures are points where either $p_t^{export} < 0$ or $p_t^{export} > p_t^{retail}$ caused by rare fluctuations in the export price. This issue is further discussed in section 7.

6.1 Supply and Demand Ratio (SDR)

Figure 8 shows the resulting SDR prices over one year for the selected municipalities.

It can be noted that the prices are very different in terms of value and variability among the municipalities depending on the residual load (i.e., the ratio of supply and demand). The variability of $p_t^{p2p\,buy}$ and $p_t^{p2p\,sell}$ can be explained by the fluctuations in of p_t^{export}. The uniform spread is cause by the aforementioned clipping of the dataset. This leads to negative prices both for selling and buying in some cases. These cases increase in all communities with high oversupply. Additionally, in municipalities with high fluctuation of demand or supply, the prices equally fluctuate. This can be seen especially in Minden and Henschtal which are supplied by wind and PV. Hofgeismar, however, has much lower fluctuations since energy is mostly provided by relatively constant hydropower and biomass in contrary to PV and wind.

In municipalities with high oversupply, prices are generally lower in SDR since in these cases the following applies: $p_t^{p2p\,buy} = p_t^{p2p\,sell} = p_t^{p2p\,export}$. This can be seen in Nieheim, which almost exclusively has high oversupply and the prices almost equal p_t^{export}. In contrary, municipalities with low supply, prices approach p_t^{retail}. Especially in Gerlingen and Henschtal this leads to very high selling prices ($p_t^{p2p\,sell}$) with almost $p_t^{p2p\,sell} = p_t^{retail}$. A special case is present in the municipality of Henschtal. Since it is almost exclusively supplied by highly fluctuating PV, the prices are low during the day and approach $p_t^{p2p\,buy} = p_t^{p2p\,sell} = p_t^{retail}$ at night.

All in all, SDR is especially viable for DER in communities with low supply since $p_t^{p2p\,retail} \gg p_t^{export}$. In contrary, for communities with high oversupply, $p_t^{p2p\,buy}$ are low and hence the SDR is viable for consumers. The more fluctuation occurs within a community, the more fluctuation can be seen in the prices. This leads on the one hand to lower planning reliability but may incentivize investments in flexibility and storage capacities.

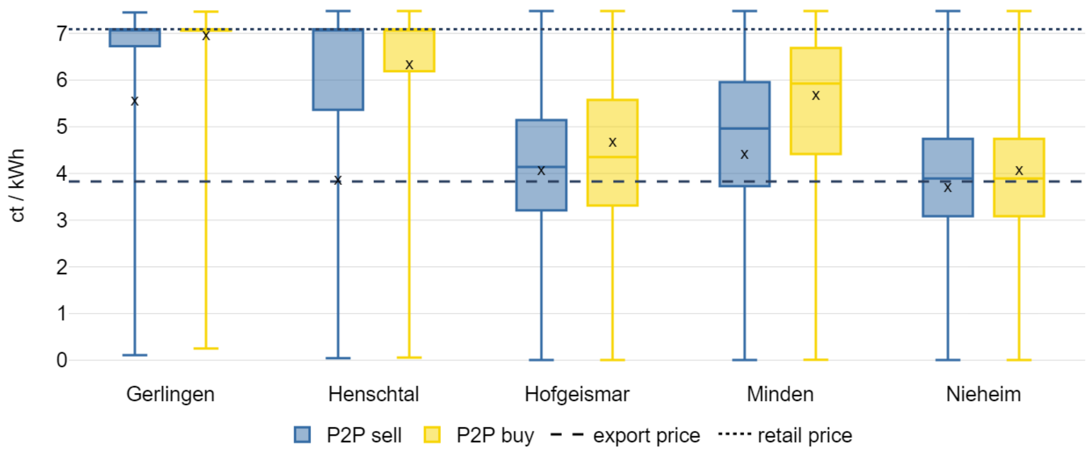

Figure 8: Resulting SDR prices for different municipalities in Germany. The P2P prices weighted by power quantities are illustrated as overlay markers. The export price depicts the average export price in the simulated year.

6.2 Mid-Market Rate Pricing (MMR)

In contrary to SDR, MMR shows much less fluctuations of the prices among the municipalities, as depicted in Figure 9.

Since the prices often approach the mid-market rate p_t^{mid} both for $p_t^{p2p\,buy}$ and $p_t^{p2p\,sell}$ instead of p_t^{retail} and p_t^{export} as in SDR for the same timeframe, this leads to more stable prices for consumers and producers alike. While this provides more planning reliability it does not incentivize investments in flexibility and storage capacities as much as SDR.

In communities with high oversupply (e.g., Nieheim) the sell price almost equals the export price ($p_t^{p2p\,sell} = p_t^{export}$) while buying prices ($p_t^{p2p\,buy}$) are equal to p_t^{mid}. In this specific case, MMR is not beneficial for suppliers and significantly more expensive for consumers than SDR. In communities with highly fluctuating supply (e.g., Henschtal) with solely PV supply during the day and no supply at night, $p_t^{p2p\,sell}$ almost always approaches p_t^{mid}. These prices, however, are not relevant to the DER (since there is no supply at these times).

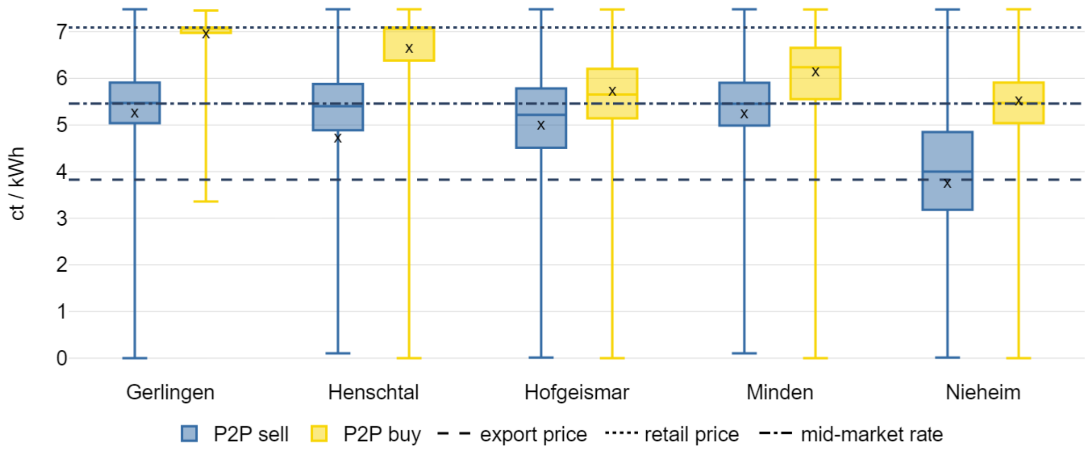

Figure 9: Resulting MMR prices for different municipalities in Germany. The P2P prices weighted by power quantities are illustrated as overlay markers. The export price depicts the average export price in the simulated year. The same applies to the mid-market rate.

6.3 Bill Sharing Mechanism (BS)

BS in simple terms treats a community like a single prosumer. Energy within the community is shared for free and resulting costs and revenues shared among consumers or producers along the predefined timeframe. In this study, the accounting period was defined as one year. This leads to overall very low $p_t^{p2p\,sell}$ since internally produced energy is provided for free to consumers. $p_t^{p2p\,sell}$ is generally lower than p_t^{export} due to its linear dependency to the self-consumption rate within the community. This behavior is depicted in Figure 10.

The pricing mechanism is especially bad from a monetary perspective for producers, because electricity is primarily shared for free. Only oversupply is sold for p_t^{export} but evenly distributed on the annual production. This yields almost no revenues for DER in communities with low or no oversupply and only small revenues in communities with high oversupply. For consumers this is by far the most beneficial pricing mechanism, since energy is shared for free and there are no costs for electricity in cases of oversupply. Due to the buy price ($p_t^{p2p\,buy}$) being limited to p_t^{retail} there is no risk for high consumer prices.

In contrary to MMR and SDR, BS does not (financially) benefit producers even over the status quo (p_t^{export}) but only favors consumers. Due to the low export prices and the complete lack of price fluctuations, there are no incentives for more production, storage (except for the increase in self-consumption for producers) or price-driven flexibility.

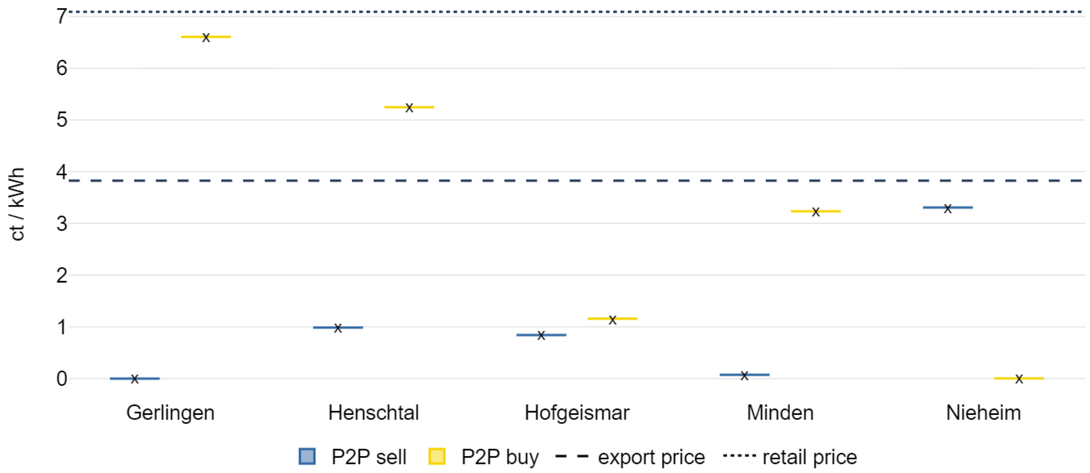

Figure 10: Resulting BS prices for different municipalities in Germany. The P2P prices weighted by power quantities are illustrated as overlay markers. The export price depicts the average export price in the simulated year.

7 Discussion

In the following, some aspects of the simulation framework are discussed. Due to the nondisclosure measures (mentioned in section 4.2), the number of buildings according to [20] is lower than in the administrative census data from [22] and therefore the number of residents and thus also the energy demand tend to be underestimated. Also, energy demand is modelled only for the private household sector, neglecting the industry and tertiary sector. Furthermore, the supply side is represented solely by RES. This is due to the fact that the main goal of the simulation framework is to analyze effects of a increasingly decentralized energy system (e.g., labeling of power quantities and guarantee of origin [47] or P2P energy sharing) where private housholds and DER are in focus. Due to possible inaccuracies in the geolocations of PV systems and the generalized census grid, the number and hence the installed capacity of PV systems also tend to be underestimated since only those are considered that spatially intersect the census grid. This issue will be addressed in future versions of the simulation framework. In addition, biomass and hydropower generation modeling is subject to certain simplifications. Regional differences in load profiles are not considered (hydropower) or on a coarser geographical level, i.e., district level (biomass). Further simplifications include constant charging power of BEV’s at 3.7 kW and simple modelling of battery capacities depending on the BEV size (small = 20 kWh, medium = 40 kWh, large = 60 kWh).

In future works, additional data and use cases to analyze effects of an increasingly decentralized energy system should be implemented and compared. These use cases include e.g., labeling of renewable energy and regional direct marketing as introduced in [47] as well as agent-based modeling of P2P trading prices. The focus of the simulation framework are private households and DER.

During this study, it has become apparent that the SDR and MMR pricing mechanisms are not robust in certain situations. Thus, at times when the export price falls below zero (e.g., due to major oversupply in the energy market) or is greater than the retail price (e.g., due to major undersupply in the energy market), these extreme values propagate and are reflected in the resulting P2P selling and buying prices. This leads to a high risk for non-flexible community members and can be prevented e.g., by a price cap or a lower resolution of propagated stock prices.

The following assumptions need to be addressed in the future:

- Currently no taxes and levies or network charges are considered within the framework.
- The municipalities were selected more or less at random, since the only thing that was considered was their noticeable difference in terms of their energy-economic characteristics. In future works representative communities should be picked in order to be able to draw conclusions about all municipalities in Germany.
- Regarding the BS pricing mechanism, different accounting periods (e.g., monthly, weekly, daily) should be considered.

8 Summary and Outlook

Digitization enables new interactions and possibilities to integrate small-scale renewable energies into the energy market. Peer-to-Peer (P2P) energy sharing is one way to connect consumers, prosumers and DER locally or with a shared goal. We showed that the economic benefit is not the only incentive for prosumers to participate in P2P energy sharing yet a vital part of it. Peers who are willing to engage in P2P energy sharing pay more attention to the whole community's benefits than the individual's.

In section 4 we introduced our simulation framework to model local energy markets and other use cases on municipal level. The simulation framework utilizes available data of different sources to reflect the real conditions in each community as realistically as possible. Due to datasets having lower resolutions than the desired household-level, we introduced multiple ways to still derive information about local site conditions, based on reasonable assumptions. This simulation framework will be improved in the future and can serve as a basis for further evaluations. These evaluations might include the distribution of regional green electricity certificates or regional direct marketing, as described in [47].

We introduced the first implemented use case in section 5 in the form of various P2P pricing mechanisms. We introduced the supply and demand ratio (SDR), the mid-market rate (MMR) and bill sharing (BS) and compared these mechanisms for five different municipalities to the status quo with static household electricity prices as p_t^{retail} and corresponding stock prices as p_t^{export}. Depending on the residual load, the times of over- and undersupply are crucial for the resulting prices. While SDR is especially viable for producers in municipalities with low supply and high demand, the opposite is true for consumers. SDR is characterized by the fact that price fluctuations are significantly greater than for MMR, which is a good incentive for additional renewables in times with low supply, flexibility and storage capacities. MMR has significantly less price fluctuations and therefore provides more stable financial conditions both for the supply and demand side. From an economic perspective, bill sharing is by far the worst mechanism for producers since surplus electricity is shared for free to the consumers. Only in times of oversupply, revenues are generated and distributed among producers. The system provides the most stability yet offers no price fluctuations and hence no incentive for additional renewables, flexibility or storage capacities.

All in all, the mechanisms show promising results to include small-scale renewables into the energy market. However, no clear winner can be identified either, making it difficult to recommend blanket pricing systems for every community without deeper analysis. In future works we will address the remaining issues of the simulation framework discussed in section 7 and implement further use cases. These include agent-based pricing models and regional direct marketing to evaluate their potentials, advantages and disadvantages.

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