Staudt and Richter
Energy, Sustainability and Society (2025) 15:6
https://doi.org/10.1186/s13705-025-00511-5

Energy, Sustainability and Society

RESEARCH Open Access

Empirical case study of a digitally enabled energy community with prosumers and P2P trading

Philipp Staudt[1*] and Bent Richter[2]

Abstract

Background An 'energy community' can add socioeconomic components to microgrids and has recently been solidified as the regulatory concept of a 'Citizen Energy Community' by the European Union. Such energy communities can further be supplemented with digital capabilities. This paper provides insights from a 13-month case study on a digitally enabled energy community with prosumers with limited ability to provide manual demand response, who were enabled to engage in peer-to-peer trading of local energy generation.

Results Long-term willingness to pay for local sustainable electricity in the market environment was lower than expected. Overall willingness and ability to provide manual demand response might be low. Participants' use of the provided digital tools were at least partly driven by their desire to control energy costs.

Conclusions Repeat interaction with the energy community's market and its inherent complexities might limit the ability of energy communities to provide technical and economic benefits. This diminishes the appeal of corresponding business models. One direction to make energy communities more attractive to regulators and utilities is the conceptualization, design, and empirical evaluation of systems that lead to low perceived complexity for participants while enabling high levels of external automated control.

Background

The global transition to low-carbon energy systems has led to an increased capacity in decentralized power generation owned by private households. More communities are gaining independence from the central power grid and are instead transforming into microgrids. Such microgrids have a long tradition in power systems research but are often analyzed from a purely technical perspective, focusing on control and balancing [43]. Increasingly, socioeconomic structures are added to these technical concepts, turning microgrids into energy communities (ECs). Some of these concepts have become so popular, they have also been defined by regulators. The European Union (EU) has termed the 'Citizen Energy Community' as an entity where local residents can own and operate power infrastructure to supply themselves with energy, ideally making their household energy mix more sustainable [61]. This EU-wide legislation is now being implemented across member states [65]. Similar legal concepts are being put to use around the globe, such as the 'Community Choice Aggregator' in the United States [44], the 'Renewable Energy Community' in the EU[34], and the 'Customer System' in Germany [41].

This idea has further gained momentum with the rise of blockchain technology (e.g., [37]), though initial expectations have not been met yet [56]. However,

*Correspondence:
Philipp Staudt
philipp.staudt@uol.de
[1] Environmental and Sustainable Information Systems, Carl von Ossietzky University of Oldenburg, Ammerlaender Heerstrasse 114-118, 26129 Oldenburg, Germany
[2] Information and Market Engineering, Karlsruhe Institute of Technology, Kaiserstraße 10, 76131 Karlsruhe, Germany

Table 1 Hypotheses and underlying assumptions from literature

Reported assumptions	Hypotheses
Local residents are willing to pay more for locally generated renewable energy [38, 64]	Given an external reference price for conventional generation, bids for local generation by participating households will be higher than the reference price
ECs support local balancing of supply and demand in the presence of intermittent renewable generation [50, 67, 79, 80]	Participants will consume more when local prices are low and will consume less when local energy prices are high
Participants will regularly engage with the EC, e.g., to adjust their preferences [32]	Users will frequently adjust their bid prices
Given an information system for observing energy consumption, households become more energy-aware [3]	Households will become more conscious of their energy consumption after being introduced to the provided information system
Users can be replaced by automated agents to increase market efficiency in LEMs [9]	Implementing autonomous agents that bid on behalf of human participants will lead to game-theoretically optimal market outcomes

increasing wholesale power prices make the concept of ECs more attractive to local utility companies [27]. Consuming locally generated electricity reduces the need to purchase energy on central energy exchanges [16]. The concept of allocating locally generated energy to households on a peer-to-peer (P2P) basis within an EC is often referred to as a local energy market (LEM) [36]. While the EC describes the overarching socio-technical system, the term LEM specifically refers to the P2P trading aspects within an EC.[1]

Proposed approach

Beyond social innovation and societal benefits, various technical, ecological and economic benefits are attributed to ECs, such as the provision of demand side flexibility and the reduction of necessary grid expansion [14]. However, whether these benefits materialize in practice is rarely evaluated. A few pilot projects have been established, focusing on various aspects of LEMs in digitally enabled ECs [72], but most did not empirically test them. This lack of empirical testing makes it challenging to evaluate the impact of a large-scale deployment of ECs and LEMs within ECs. In this study, we report on the empirical results of the digitally enabled Landau Microgrid Project (LAMP). We provide insights into how digitally enabled ECs and LEMs within these ECs can realize technical and economic benefits for the energy system and market, which might be translated into corresponding business models [14]. We also offer insights into the utility of digitally enabled ECs for participants beyond technical and economic considerations.

Hence, we add novel insights in the following ways: (1) The project ran for almost 2 years, comprising a 6-month introductory phase, a 13-month active trading phase, and a 5-month evaluation period during which consumers could task a trading agent to automatically place bids for them. To the best of our knowledge, this is the longest study of its kind and offers unprecedented longitudinal results. (2) This is the first study of its kind with a mixed-methods approach, combining quantitative data with extensive qualitative results from semi-structured interviews with participants. This offers additional insights into user interactions with ECs, allowing for practical implementation recommendations. And (3), this is the first study of its kind to empirically evaluate an automated computer bidding agent interacting with human trading partners on an LEM. Table 1 summarizes the technical and economic assumptions about ECs, provides references to corresponding literature, and presents our hypotheses.

This paper offers insights into participant behavior in digitally enabled ECs with integrated LEMs, informing future research and development about ECs. Some results of this case study are triangulated with a similar study [73] that reported on the Quartierstrom project, which had objectives similar to the LAMP. This allows us to form a first academic consensus using case triangulation over two distinct and independent studies in different settings [76]. The results of this triangulation are summarized in Table 4 in Sect. Discussion.

Related work

Definitions and political dimension While microgrids have traditionally been installed in remote locations without electricity grid infrastructure, they are increasingly being deployed in existing grids [71]. The EU has added a social layer to this formerly solely technical construct by introducing the concept of Citizen Energy Communities [61]. The European Commission defines a Citizen Energy Community as a legal entity that: "(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including

[1] A draft of this study has been published as a preprint [54].

municipalities, or small enterprises; (b) has for its primary purpose to provide environmental, economic, or social community benefits to its members or shareholders or to the local areas where it operates, rather than generating financial profits; and (c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services, or charging services for electric vehicles or provide other energy services to its members or shareholders;" (Article 2 of the Electricity Directive, [47]). While we view ECs more broadly in this paper, our case study is closely related to this definition and regulation. In reaction to the introduction of this legislation, various member states are now discussing and implementing ECs and LEMs, but the concept is also popular in the UK and the US (e.g., [5, 11, 13, 50, 55]). There are various definitions for LEMs (see, e.g., [37, 40]). For this study, we consider LEMs as the allocation framework that enables and facilitates the trading of energy and associated services between the diverse participants within a microgrid through an auction-based platform [63]. On this platform, the local matching of supply and demand is performed by predefined algorithms that calculate prices based on bids submitted by market participants. The operator of such platforms is not clearly defined. It might be the local energy supplier as in our case or it might be an autonomous system that is run on a blockchain [37].

Energy communities ECs and variants of this concept have been extensively studied over the last few years, mostly from a conceptual perspective while empirical behavioral research remains scarce. A review of LEMs, including a technical perspective and role descriptions, is provided in [62]. For a broader discussion of LEMs and its associated concepts, we refer to [27]. A typology of ECs is provided in [23]. A review of international efforts to strengthen community energy can be found in [30]. The impact of LEMs on power systems is addressed in another review [18]. An overview of auction clearing approaches is given in [77].

Societal objectives of energy communities ECs have been shown to add societal value across several dimensions. One European Commission study identified that ECs possess social innovation potential [14]. It has further been argued that community engagement in ECs increases the acceptance of renewable projects [70], a sentiment that has been reaffirmed [29]. However, some have pointed out that acceptance might depend on the specific configuration of the EC [5]. Energy communities are also perceived as tools to help finance the sustainable energy transition [55]. ECs support the energy transition by incentivizing the installation of more residential renewable resources, thereby contributing to the targets of the Paris agreement [71]. While this is not their exclusive purpose, it aligns with the objective of corresponding regulatory tools. LEMs enable participants to exchange local generation [31], driven by a range of participant objectives (see [38] for an overview). Using auctions [77], LEMs serve the basic functions of tariffs by encouraging electricity consumption when market prices are low, and discouraging it when they are high [10]. Broadly, ECs represent a facet of the so-termed smart grid evolution, introducing more communication technology into present distribution grids [75]. From a technical perspective, some have detailed how ECs can integrate into the existing energy system [78], while others highlight social innovations of ECs [12].

Balancing objectives of energy communities Schmitt et al. [57] and Wagner et al. [69] discussed the integration of ECs into the energy system, noting their potential benefits for the system as a whole. Zhang et al. [78] proposed a P2P architecture for microgrids to improve the local balance of demand and supply. Zwickl et al. [80] posited that ECs can add flexibility to national power systems. Others highlighted ancillary services as a potential offering from ECs [66]. Parag et al. [46] presented ECs as an especially appropriate alternative for integrating prosumers into the energy system. Additionally, LEMs are viewed as an income stream for ECs, made possible through local allocation via an auction mechanism [63]. And finally, Morstyn et al. [40] concluded LEMs can indeed operate as a unified entity in the power market, taking on the role of a virtual power plant capable of providing energy services. To add, simulations of integrating multiple microgrids and their projected flexibility in the wholesale energy market have been detailed [31].

Participant objectives of energy communities The existing body of literature has explored various motivations for individuals to join ECs and LEMs, particularly from the perspectives of consumers and prosumers. Multiple studies revealed a geographic or community preference for energy generation among groups of consumers, which LEMs can accommodate. For instance, Kaenzig et al. [25] discovered consumers favor smaller, local providers. Mengelkamp et al. [38] determined that feeling a 'sense of community' plays a key role in the decision to participate in an EC. Interestingly, Soeiro et al. [60] reported that the consumers' motivation to join an EC is largely influenced by normative factors (discussed below), with financial considerations being less impactful. Other researchers posited that gaining independence from major energy companies serves as a significant motivator [50]. Woerner et al. [74] asserted that LEMs can potentially increase revenue for local prosumers, making an investment in renewable energy generation more appealing.

Importantly, most assumptions regarding the technical and economic advantages of ECs have not been thoroughly empirically validated. Due to the high costs and intricacies associated with empirical case studies, many researchers opt for simulation studies, which theoretically demonstrate flexibility potential or increased revenue from renewable installations. Field-based case studies typically produce limited sample sizes. As a result, multiple studies need to be cross-referenced for a more comprehensive understanding. To the best of our knowledge, the only other empirical EC case study with an associated LEM is on the Quartierstrom project [73]. Much like our study, they grappled with the challenges of limited sample sizes and other obstacles intrinsic to empirical research. However, comparing the two studies facilitates the triangulation of findings [76]. Additionally, leveraging a mixed-methods strategy, we incorporate qualitative insights from interviews with participants, thereby enriching the interpretation of our quantitative data. Uniquely, we posit that our research is the inaugural effort to document the empirical assessment of automated trading agents in LEMs that engage in real-world transactions with human participants. We underscore that our emphasis is not on the broader societal benefits or innovations potentially instigated by ECs. Consequently, our study should be perceived as an exploration of the business models underpinning ECs, with the objective of fostering their sustainable economic management and prompting regulators to devise favorable EC guidelines (also see [14]).

Methods

The LAMP is an empirical field project of an EC situated in a southwestern German city. The project is located in a residential neighborhood with only one connection point to the energy distribution grid. Power is delivered to households via a local areal grid owned by the local utility company. Notably, this grid is not operated by the distribution grid operator since it is not part of the public grid; instead, it is operated by the unregulated subsidiary of the local utility company. This setup offers more regulatory freedom, as this technical construct makes use of a regulatory exemption [1]. Energy generated and then consumed within this areal grid has fewer levies imposed on it. Most importantly, no network tariffs are charged for locally generated electricity. In total, the discount on locally generated energy amounted to 13.31 EURct/kWh or roughly 45% of the then average electricity price [39]. This difference can be used to subsidize the exchange of locally generated power between neighboring households.

Within the local areal grid, solar PV panels with 23 kWp capacity and a CHP with 50 kW electrical and 85 kW thermal capacity are owned and operated by the local utility company. Additionally, three participating households installed residential PV panels during the project, becoming themselves prosumers. Energy generation from these sources was dynamically priced throughout the project so that consumers were charged resulting market rates in corresponding 15-minute intervals. Whenever the generation from these resources is insufficient to satisfy demand in the areal grid, additional energy is bought from the public grid. During the project, this additional supply was continually priced at the flat per kWh rate that households were subscribed to. Accordingly, any savings from lower energy prices could only originate from locally consumed generation. The CHP, controlled by the local utility, responds to the local heat load of a district heating system. It is fueled by natural gas, making it a local yet non-renewable resource. Excess generation is fed into the distribution grid. There are 118 connection points (i.e., households) within the area. The initial information and recruiting event was facilitated by the local utility in Q4 of 2017. All local residents were informed by mail about the local event and around two dozen people attended. We did not record whether these attendees belonged to different households. The incentives provided were: (1) an Android tablet worth about 100 Euros, (2) potential electricity savings from lower electricity prices within the project (which ended up ranging between 25 and 120 Euros), and (3) the installation of smart meter hardware along with a mobile app. Eleven households joined the project. This 10% participation rate is quite modest. It should be noted that these households self-selected for the project, thus introducing self-selection bias. We did anticipate them being more interested in local (renewable) energy generation and more eager to engage with their energy usage. This potential bias should be considered when interpreting positive outcomes. While participants were aware of the project's digital tools, not all were tech-savvy. At project start, the team individually introduced participants to the digital EC app's functionality as needed. At that time, all participants had electricity supply contracts with a set flat rate per provided kWh. Details on the participating households are shown in Table 2. None of the households owned electric vehicles, heat pumps, or battery storage. This detail is mentioned to emphasize the limited potential for demand response among participants. Throughout the project, we complied with EU data privacy laws. All participants signed data release forms that were approved by data privacy experts from the utility company. Furthermore, all data was exclusively stored on servers in the European Union.

During the project, we did not solicit participant feedback. Instead, we monitored their bidding behavior and

Table 2 Participant details

Participant number	Living arrangement	Household members	Age of main particpant
1	Single-family home	3	40
2	Apartment	1	72
3	Single-family home	4	48
4	Single-family home	3	50
5	Apartment	2	53
6	Single-family home	2	66
7	Apartment	2	65
8	Apartment	2	57
9	Apartment	1	55
10	Apartment	2	48
11	Apartment	2	72

conducted interviews post-trading phases in September 2020 (see also the project timeline in Fig. 4). Each of the 11 participating households was represented by one interviewee. These semi-structured interviews were conducted via phone (due to the COVID-19 pandemic) and lasted between 45 and 120 min. Interview topics included: (1) general motivation and project experience, (2) the market mechanism and electricity sources, (3) trading phases and reports, and (4) the mobile application. While each interview started with the same set of questions (see Appendix), we also allowed for flexibility in the conversation to better engage with the interviewee.

Digital infrastructure At the beginning of the project, participating households were equipped with digital electricity meters that featured a Long-Range Wide-Area Network (LoRaWAN) communication module, which was installed within the neighborhood for the project (see [33] for more details on LoRaWAN).

The participants accessed data using a mobile and web-based application specifically developed for the project. Screenshots of the application, providing insights into its functional design, are shown in Figs. 1 and 2. The application was pre-installed on the Android tablet provided, and the app functions were explained to the participants by the project team. However, participants could use any device to access the application. The application required participants to log in with unique credentials that were

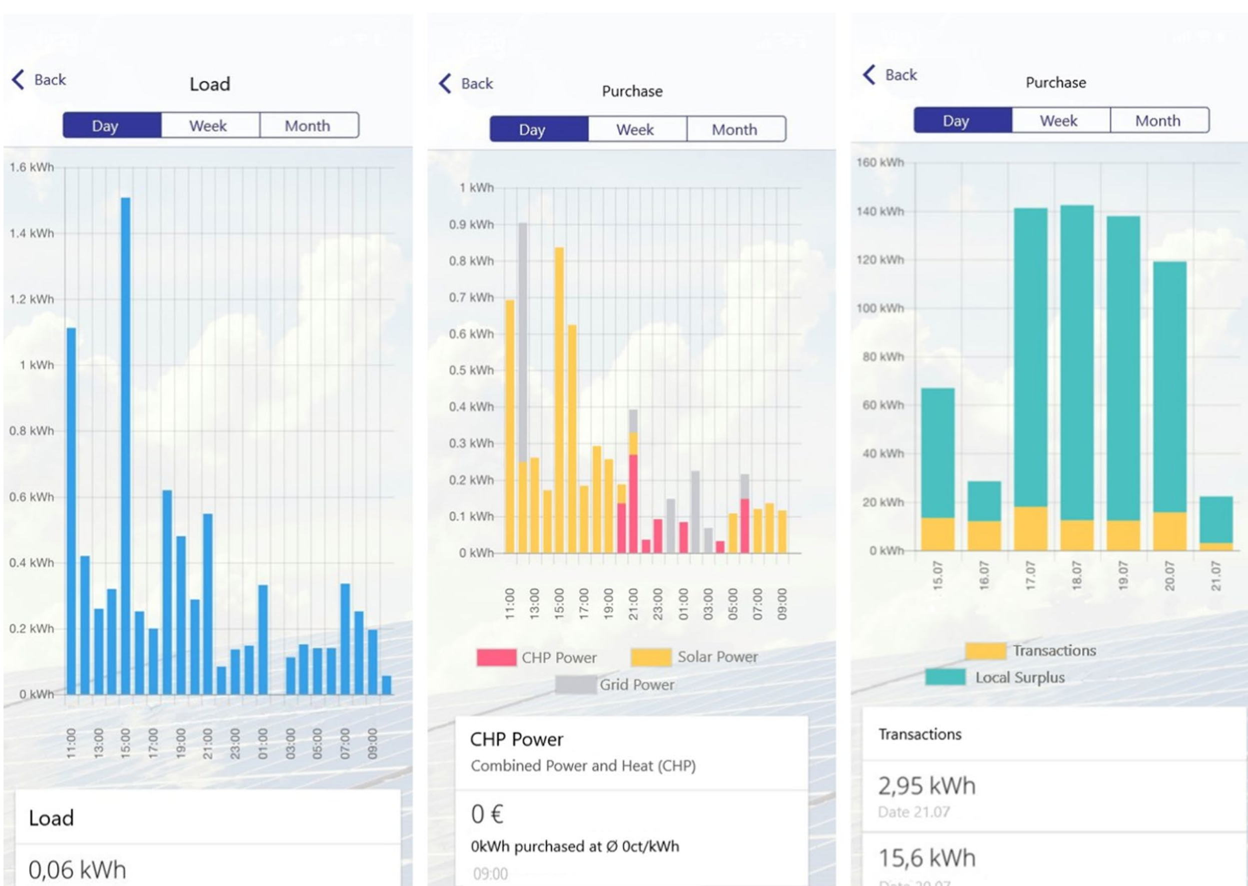


Fig. 1 Consumption reporting functionality of LAMP application

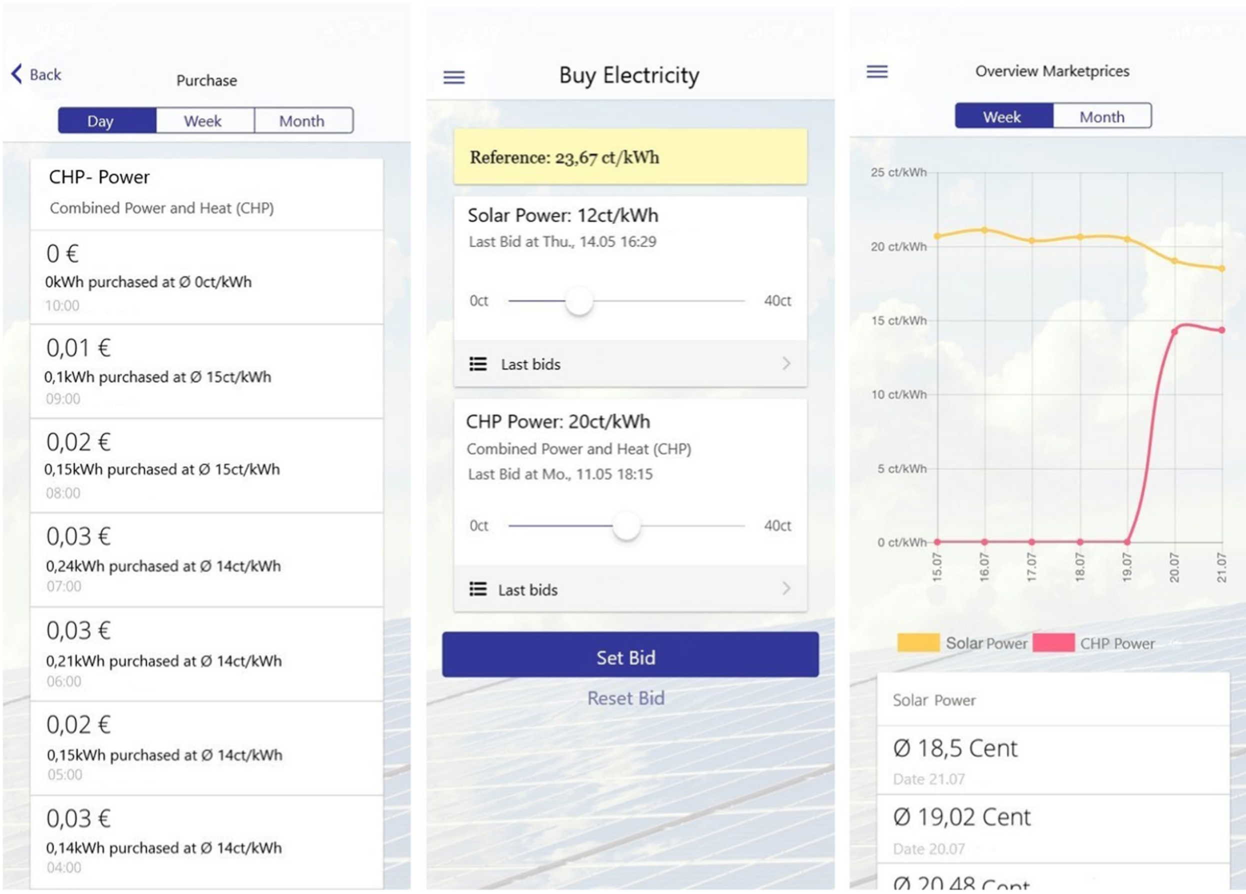


Fig. 2 Price and cost reporting functionality of LAMP application

provided to them, allowing them to see their household's energy consumption as well as the generation from system resources, namely the PV and CHP generation. Furthermore, the app allowed users to set their bid prices to participate in the LEM. For a more detailed description of the IT infrastructure of the project, see [53].

Local energy market design The LEM mechanism was designed to allow for the communication of a broad spectrum of preferences. Participants were enabled to bid separately for different sources of electricity. This means that participants were able to set a willingness-to-pay for local PV generation and local CHP generation. This approach creates several market places and individual but connected knapsack problems for the fulfillment of the participants' demand. This meant that we had to decide how to integrate several local energy sources into one market. To solve this, we combined a uniform-price market clearing with an approach from voting theory, the Borda count [19], to create two separate but interdependent markets. We treated participants' bid values as an order of preference similar to a vote between several candidates, where the most preferred candidate is assigned the highest score and scores then decrease going down the ranking. In other words, if a participant bid more for local PV generation than for local CHP generation, local PV generation would be assigned a Borda score of 2 and CHP a Borda score of 1. All Borda scores of all participants are then added to decide which market is cleared first. This way, the energy generation preferred by the majority of the participants is allocated to consumers first. The price on each market was then set by the highest still accepted supplier bid. In later trading phases, we changed this mechanism so that the price was set by the lowest still-accepted demand bid (as shown in Fig. 3). We explain this further below in the section on trading phases. A detailed evaluation of the market mechanism is provided in [52].

The market was cleared every 15 minutes. The local utility set the price for local PV and the power generation from the CHP. The average ask price over all bidding periods for PV was 21.6 EURct/kWh and 13.9 EURct/kWh for energy from the CHP installation. Figure 3 shows an excerpt of the PV generation values of July and August 2020 in 15-min resolution as well as the market clearing

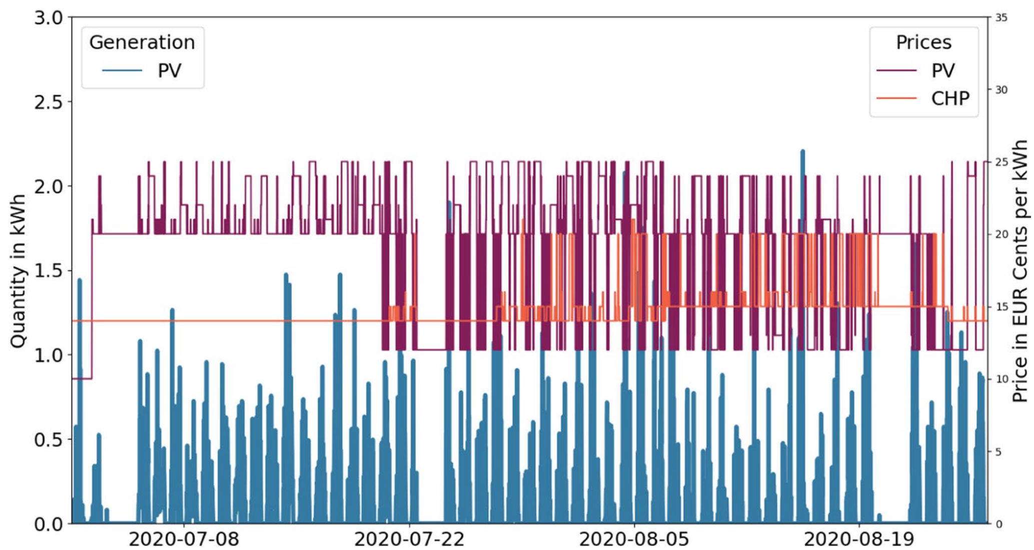


Fig. 3 Local PV generation and market prices in the LAMP

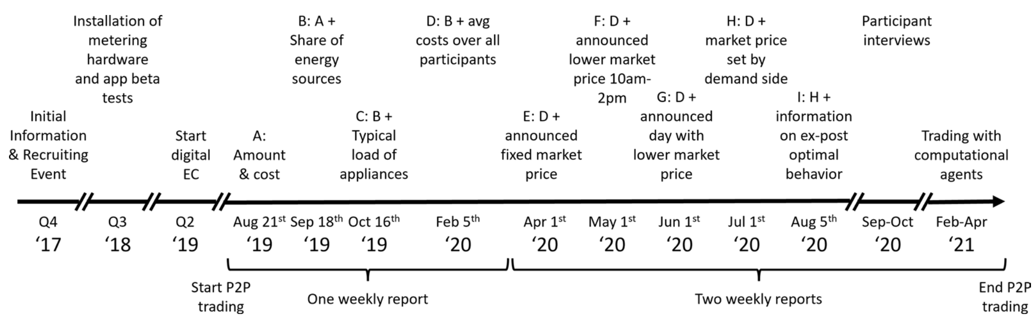


Fig. 4 Overview of the project timeline of the LAMP

prices, to provide an impression of the market dynamics.[2] This time resolution is equivalent to the lowest traded time resolution on the European wholesale electricity markets and is therefore relevant for the local utility. As long as consumption is balanced within a period of 15 min, no additional energy has to be procured. Participants were able to place bids between 0.0 and 40.0 EURct per kWh. However, the feed-in tariff for residential solar PV of 11.0 EURct/kWh and the residential electricity tariff of 23.7 EURct/kWh gave some reference for the bid prices. We further reflect on this in regard to the bidding behavior in Sect. Discussion.

Trading phases and hypotheses In order to test participant responses to our interface and market design choices, we performed nine dedicated trading phases with varying features and incentives. These trading phases usually ran for a month but would sometimes be extended to account for technical difficulties. For instance, the LoRaWAN antenna was damaged once during a storm, which impacted data transmission and the trading phase C was extended to ensure proper interaction with the design. Figure 4 provides the timeline of the project. Note that while the trading phases were short, the general capabilities of the digitally enabled EC were upheld over the entire time (mobile app with real-time access to energy consumption, dynamic market based pricing of locally generated electricity and costs and corresponding reports). However, we cannot claim any results on long-term effects of any individual trading phase. Figure 4 documents all trading phases including the duration of the phases as well as the number of reports that were sent to participants each week. The reports were a distinct feature that was included in the design after specific feedback of participants. They summarized the market behavior and performance of participants over the period since the last report and gave us

[2] The three missing days in PV generation were caused by short outages of the LoRaWAN data transmission.

the opportunity to communicate targeted information. One example report is shown in Fig. 7 in the appendix. These features as well as the mobile app are not necessarily features of ECs and can similarly be implemented for individual agents. However, in our case, they supported and incentivized the consumption of locally generated electricity and are therefore a feature of digitally enabled ECs. Until trading phase H, the price was always set by the supply side. As we controlled the asking prices of the utility-owned resources, this allowed us to set specific incentives through price signals. The first trading phase A introduced the reports, where individual consumption and costs were communicated. In trading phase B, the individual energy mix was added. In trading phase C, we intended to increase energy literacy of consumers and added information on the electrical loads of specific household appliances. Previous studies have reported a change in energy consumption behavior with an increase in energy literacy [59] and reported positive effects on energy savings [22]. In trading phase D, we showed participants how they compared to their peers. There are mixed results from such an approach [35]. Throughout these first four trading phases, we expected some reactions to the information that was provided to participants such as changes in bidding prices or an adjustment of consumption. Several studies have stated that frequent interaction between participants and ECs is required to create a lasting effect (e.g., [32]). Furthermore, we expected participants to favor local PV generation over CHP generation and a willingness-to-pay a premium for local PV generation. The latter was reported by participants before the project, and previous research often reported on a higher willingness-to-pay for renewable generation (e.g., [8]). In phase E, we made the market more dynamic. We fixed the asking price of the utility-owned PV at the lowest price that was accepted during the previous reporting period and announced that price with the report. In order to evaluate the willingness to shift load, we then introduced temporal differences in the prices. One common advantage of ECs is frequently reported to be an improvement in congestion management in the distribution grid [49] and local balancing [78]. This can only be achieved through load curtailments, increases or load shifting (i.e., demand response). We therefore investigated whether such reactions can be reasonably expected from consumers. In trading phase F, we lowered the asking prices of the utility-owned PV generation between 10am and 2pm to coincide with the expected PV generation peak essentially introducing a form of time-of-use pricing. This design allowed us to assess the intraday willingness and ability to shift load. To also assess whether consumers are willing to shift load between days, we then introduced low-priced days in trading phase G, where we lowered the utility PV asking price on the day with the most expected sunshine hours, again to peg the price somewhat to the realities of PV generation. In trading phase H, the price was then set by the last served consumer bid, which again introduced a somewhat more dynamic pricing because there was more competition on the demand side with 11 participants as compared to only 4 generators (the utility and three prosumers). Finally, in period I, we also communicated what the optimal bidding behavior would have been during the last reporting period in order to incentivize bid changes. We recorded consumption, generation, and bidding data for all periods.

Results

Before we report and discuss the results, we want to point out that any results for this specific case with a total of 11 participants have to be evaluated carefully. We are aware that the context plays a large role and that the small sample size does not allow for generalizations. We triangulate our results with the Quartierstrom project [73], where possible, to allow for a better generalization. The corresponding results are summarized in Table 4 below. We begin by reporting on the results from the quantitative analysis of bidding and consumption behavior over the project duration. We further enrich these results here and in the following Sect. Discussion with a qualitative evaluation based on the semi-structured interviews [4] that were conducted with participants after the trading phases had ended. This mixed-methods approach allows us to better understand the reasoning behind certain participant behavior. Furthermore, it allows us to explore the perceived value and the use of the system by participants. As the digital EC system provides an array of affordances, our results elucidate how participants benefit from digitally enabled ECs. We first look at user interactions with the market. We then focus on the user interaction with the provided digital interface. In the following Sect. Discussion, the results are further discussed and compared to previous results from the empirical EC case study Quartierstrom [73] as shown in Table 4.

User behavior on the local energy market

In this section, we discuss three particular aspects of quantifiable behavior observed within the LAMP that are noteworthy. Namely, we shed light on the bidding behavior regarding local renewable resources, the reaction to price signals in terms of demand response and the overall frequency of interaction with the EC. We frequently refer to Fig. 5, which displays the consumer bids over the trading phases for PV generation and Fig. 6, which shows the bids for the local CHP generation. The prosumers are excluded from these figures because they had to be

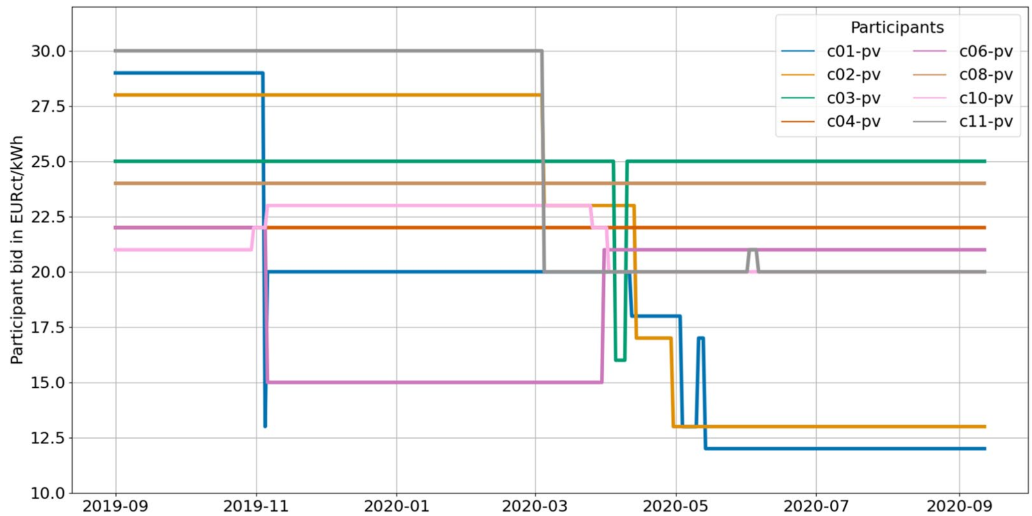


Fig. 5 Consumer bids for local PV over all trading phases

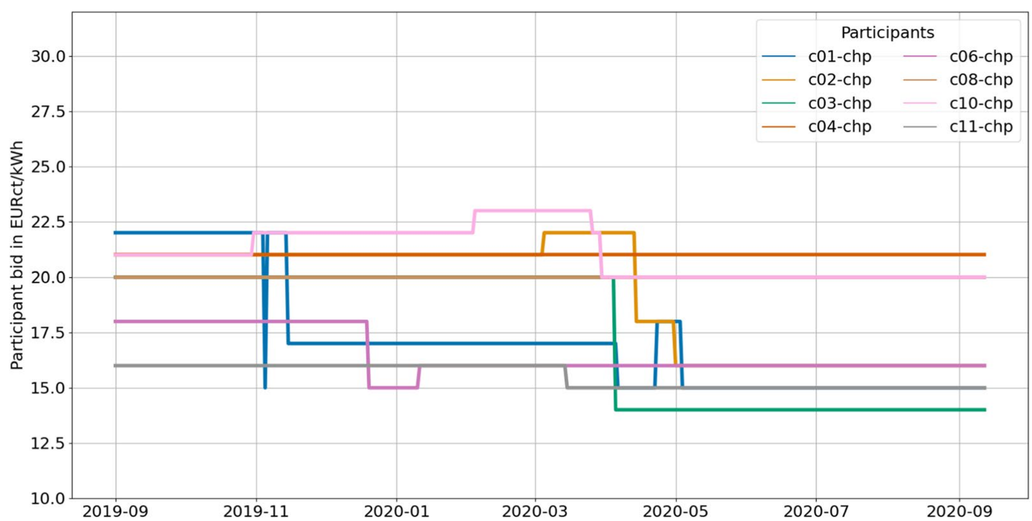


Fig. 6 Consumer bids for local CHP over all trading phases

disconnected from the IT infrastructure for the time during which their PV panels were installed (December 2019–April 2020) and the corresponding infrastructure was updated. While we mostly focus on the quantitative results in this section, we validate them with additional insights from the semi-structured interviews further discussed in Sect. Discussion.

Willingness-to-pay for local renewable energy All participants stated they would be willing to pay a premium for local renewable energy before the project began. With the start of the trading phases, 5 out of 8 consumers and 1 of 3 prosumers (who at this point were still consumers) were still bidding above the reference price of 23.7 EURct/kWh. Throughout the project, we observed a negative trend with regard to the willingness to pay a premium for local renewable energy as shown for the consumers in Fig. 5. While at the start of the trading phases, the average bid for solar PV of the consumers was still 25.1 EURct/kWh and therefore above the reference price, it declined by 5.0 EURct/kWh over the duration of the project to 20.1 EURct/kWh in September 2020, below the reference price. By then, only two consumers and none of the prosumers were still willing to pay a premium for local PV. PV generation was valued higher than CHP energy, as is evident when comparing Figs. 5 and 6. This means that the PV market was always cleared first and

Table 3 Summary of evaluation of demand response

Trading phase	Benchmark	Participants with expected behavior	Avg. demand change in low-price period (%)
F	Previous week	8/11	0.6
F	4 previous weeks	6/11	0.5
G	Previous week	1/11	−11.8
G	4 previous weeks	1/11	−15.8

the Borda count mechanism became obsolete in this case. Similar to PV, the bid prices for CHP decreased over the project's duration from an initial average of 19.7 EURct/kWh to 17.1 EURct/kWh. These results indicate that participants were not willing to pay a premium for locality. Across all trading periods, all bid prices of all participants for local CHP remained below the reference price.

Demand response Shifting demand to alleviate congestion in the distribution grid or for the local balance of demand and supply are two prominent technical arguments in favor of ECs. We therefore focus on whether local price signals led to consumption shifts. Note that we are considering manual consumption shifts here as none of the participating households operated any type of load automation that managed an electric vehicle or a battery storage, to name two examples. In order to assess whether the participants reacted to price signals by shifting demand in the LAMP, we performed trading phases F and G, where the asking prices for the largest PV installation changed within a day and between days, respectively. During the lower priced periods, we set the price for generation from the utility PV installation to 10.0 EURct/kWh and to 20.0 EURct/kWh during the high priced periods. This price difference corresponds to 100 EUR/MWh on the wholesale market. Due to the low sample size, we had to compare data within-subjects. We chose to create benchmarks based on past behavior. We benchmark the consumption of each participant against the one week directly prior to the trading phase and to an artificial week that is the average of the four weeks prior to the trading phase.

For phase F, we calculate the relative amount of consumption during the low-priced time window as the share of the total daily consumption and then compare these shares between trading phase F and the benchmark weeks. This corrects for a general increase in consumption, possibly caused by weather events. For phase G, we simply compare the total consumption on the cheaper priced days against the total consumption on the benchmark days. Table 3 provides a summary of the results of both trading phases in regard to both benchmarks. Negative values in the last column represent results counterintuitive to what we had expected, which is that participants would respond with an increase in consumption to lower prices.

Data suggest that some consumers have shifted their demand to the lower priced periods within a day as tested in trading phase F. Six participants consumed a higher share during the low-priced periods within the day with regard to both benchmarks. As expected, lower prices led to a higher consumption during the low-price period. However, for two consumers the comparisons to the two benchmarks (week previous to the trading phase and average of the 4 weeks prior to the trading phase) point in opposite directions. They consumed more with regard to one benchmark but less with regard to the other. Three participants consumed less during the low-priced periods with regard to both benchmarks, which is counter intuitive.

We could not observe a willingness to shift demand between days as tested in trading phase G. Of the 11 participants, 10 show an average decrease in consumption over the lower priced days for both benchmarks. No participant shows an individual increase of consumption on more than three of the eight lower priced days. This suggests that load shifting between days is more difficult to achieve. Interestingly, in the interviews after the trading phases, prosumers self-reported to have shifted their demand into times with more (assumed) generation from their solar PV installations. One prosumer stated that:

> *"We do pay attention to moving the consumption into the sunshine hours."*

Ableitner et al. [2] reported similar statements from participants indicating that they would be willing to shift their consumption to sunshine hours, which was not empirically tested. We therefore compared the share of daily consumption of prosumers during sunshine hours from 9am to 6pm during the months of May and June between the years 2019 and 2020 because the PV panels of all prosumers had not yet been installed in spring 2019. We did not find a relative increase in consumption during sunshine hours. In fact, for all three prosumers, this share had slightly decreased. This is in line with [45] and [42], which both reported little or no behavioral change when consumers become prosumers.

Frequency of interaction with the market We further assess the interaction with the system in terms of bidding activity. Higher activity is not necessarily good or bad but gives an indication of how engaged participants were with the digitally enabled EC. Furthermore, it has been argued that the engagement of households is an important factor for the energy transition to succeed [58]. The bidding activity in terms of individual bid changes exhibits a large variance. The exact numbers of bid changes of the eight consumers are (12, 8, 7, 4, 4, 3, 0,

Table 4 Comparison of results corresponding to the stated hypotheses between the LAMP and [73]

Concept	Results from [73]	Results LAMP
Willingness-to-pay for local renewable generation	Even though a majority stated to be willing to pay a premium for locally generated renewable generation, almost all participants set bids below the displayed reference price of the utility	All participants stated before the project to be willing to pay a premium for local renewable generation. Over time, all but two rather inactive participants lowered their bid prices for local PV generation below the reference price
Participant activity in the EC	Participation was heterogeneous. The majority of recorded activity occurred in the beginning of the project. Some participants never interacted with the market	There were bursts of activity while at the end of the project participants did no longer interact with the system. Overall, activity was low with an average 4.5 interactions per participant over 13 months
Use of the information system	Appreciation for monthly reports. A majority used the app for market-related data [2]	Monthly reports were the main medium of interaction with the system. Participants asked to still receive reports after the project ended. The mobile application was used when reports indicated extraordinary values
Demand response	Several participants stated to have made efforts to consume during sunshine hours. This was not further evaluated. No differentiation between consumers and prosumers. Local generation often had to be fed into the grid	The data suggest some within-day demand response. However, consumers stated not to have reacted to prices even though they represented differences of 100 Euro per MWh. Prosumers stated to adjust to sunshine. Quantitative evaluation did not confirm this
Market understanding	Bid prices were reduced over time, which indicates that the market mechanism was not understood. A majority of respondents of a survey among participants correctly responded to questions in regard to the market mechanism	Participants stated not to have understood the market. Particularly, participants noted that changes in their bid prices did not result in different market outcomes. Participants reported that it influenced their interaction frequency with the system
Automated bidding	35% of users prefer not to have to set prices vs. 30% prefer to set prices themselves [2]	Automated bidding was directly implemented and led to a reduction in energy costs. Full automation of bidding of all participants might be better represented by a tariff structure

0). The adjustments can be seen in Figs. 5 and 6. Hence, on average, there were roughly three bid adjustments per month overall. The level of activity seems small given that participation in the EC was voluntary and that participants were reminded of the EC weekly and sometimes bi-weekly through the personalized market reports. The reports had a notable effect. At least 50% of all bid changes of every consumer occurred less than 24 h after a report. On average, 74% of all bid changes occurred less than 24 h after a report. Prosumers, whose bidding activity was not recorded from December 2019 to September 2020 while the PV panels where installed and the technical installations were adjusted, showed more bidding activity. On average, the three prosumers each changed their bids two times per month and the bid changes are rather evenly distributed among the prosumers and also strongly linked to the weekly reports.

User interaction with the information system

We now focus on qualitative results from the semi-structured interviews with the participants on the use of the digital capabilities of the LAMP. We particularly focus on the perceived usefulness of the different features of the mobile and web applications and how users used and interacted with these features. We also briefly reflect on an additional experiment with an automated bidding agent that was performed over 2 months from February to April 2021 within the LAMP.

Use of the information system In the interviews, we asked participants for various components of the web and mobile LAMP applications, namely the visualizations of consumption, energy mix, costs, and bid interface. Users reported deliberately turning appliances on and off to observe the power consumption. For instance, one participant stated:

> *"I was surprised by how much the kettle consumes. So, we have already gained insights, which we have then tried to incorporate into our everyday life."*

This would have been easier with a higher data resolution. Our intention with the app was mainly to provide an interface for trading energy. However, the features the app provided were used differently by participants. For instance, another participant reported on insights into the load of a dehumidifier:

> *"The thing needs an insane amount of electricity, although it is not that big. For me, one realization was that when the humidity is at 40-50%, that's when you turn it off."*

The cost visualization was criticized for being too detailed. Therefore, participants resorted to the reports for this information. The reports were praised by all participants. According to their statements, it was the feature they most interacted with. It enabled a low threshold interaction with the EC and participants reported to only have reacted or to have looked at the app values in detail if the report came up with unexpected results for costs, consumption or energy mix. For instance, one participant remarked:

> *"If I'm being honest, I always take a quick look at the report and then just check the amount. And only if it is remarkably low or high, then I look at what could have caused it. If it's okay, I don't look too closely."*

After the project ended, several users asked whether we could still provide the reports. This shows the high utility of this feature, which in essence is simply a more frequent billing procedure with detailed consumption values. This shows how digitally enabled ECs can deliver value with relatively easy tools. It can be argued whether these features are actually EC features. However, they do support the local integration of renewable generation and create a common understanding of the system. Participants furthermore found the LEM bidding interface easy-to-use because it featured a slider and displayed the reference grid price. Participants perceived these features as helpful. Participants also reported to have had problems understanding the market mechanism and quickly became frustrated with it. One participant suggested we use automated agents that would trade in his place.

Implementing bidding agents As also suggested by [2], we developed an autonomous computer agent to trade in place of each participant on the solar PV market of the LAMP using deep reinforcement learning. A similar approach in a simulated environment has been described in [15]. To the best of our knowledge, we are the first to report on the empirical field implementation of such an agent, trading with otherwise human participants. We use a dueling deep Q-Learning architecture for the agent. A detailed description of this algorithm is beyond the scope of this paper. To summarize, the algorithm learned to set prices optimally based on past market interactions. The agent is implemented for one of the two participants that never changed their bids throughout the project duration with his consent. We compared the agent's performance against the virtual performance of the participant, had he continued with a static bid of 12.0 EURct/kWh. The field experiment ran over a 2-months period from February to April 2021. With the autonomous agent, the participant reduced his average electricity costs by 0.2 EURct/kWh from 16.4 EURct/kWh to 16.2 EURct/kWh during the periods with local PV generation. These are the only relevant periods as the autonomous agent does not influence the prices in other periods. This very small reduction can be attributed to the fact that the participant would have bid 12.0 EURct/kWh in the absence of the autonomous agent. Bidding a value close to the lower bound of the market price, which is the feed-in tariff of 11.0 EURct/kWh, is already a good strategy because it leads to low market prices whenever supply exceeds demand. This strategy can only be slightly improved by bidding more in times of a supply shortage and bidding a little less in times of excess supply in which the agent succeeds.

Discussion

This section seeks to validate some of our results using interview statements and compares them to [73]. Table 4 provides a summary of this.

Willingness-to-pay for local renewables One noteworthy result of the case study is that the willingness to pay a premium for local PV generation faded over time. All participants had initially stated to be willing to pay such a premium. This result is in line with the results in [73], where the authors observe the same tendency. One possible explanation is the interaction with a market in general. Previous research has shown that when interacting with a market, participants regard the market outcome as fair and do no longer reflect on the moral implications [20]. It is therefore possible that previously normatively motivated consumers became financially motivated. Another reason could be the display of the reference grid price in the bidding interface. This is supported by participant statements. One participant mentioned that

> *"You would certainly try not to pay more [than the reference price]."*

This does of course contradict initial statements on the willingness to pay a premium. Woerner et al. [73] ascribed this to a social desirability bias, i.e., participants felt in the survey that it is the socially normative behavior to state a higher willingness-to-pay for local renewable generation. However, this also implies that participants would then bid below the reference price from the start of the project. Further statements strengthen the hypothesis of the influence of the reference value, which can plausibly be explained with the anchoring effect [21], which states that people are influenced by information given prior to a judgement or decision. One participant noted that:

> *"Yes, that [reference value] helps me. [...] And I have stayed under it, also because neighbors have said that they have stayed under it, too."*

This reveals another social issue. As others remarked to have bid below the reference price, it became socially acceptable to do the same. This is in line with the results in [6], where the authors found that social considerations play a major role in the decision to pay for sustainable energy. Furthermore, Woerner et al. [73] also displayed a reference price, which further strengthens this hypothesis. It is also possible that when constantly confronted with the question of paying a premium, participants at some point decide that they had done enough. The described effects might also have interacted. In any case, our results indicate that LEMs within ECs, depending on their design, do not necessarily incentivize renewable capacity expansion through a higher willingness-to-pay for local renewable generation. One possible remedy is to reduce the amount of interaction with the market, a suggestion that we come back to in the remainder of this paper. If, for example, participants only had to decide once a year on the premium they would be willing to pay, this might decrease the diminishing effect on bid prices of the displayed reference price.

Intraday and between-days demand response Manual demand response has long been critically discussed. In terms of energy savings, Desley et al. [17] noted that it is still largely unclear what type of feedback can encourage energy savings. A field evaluation of reported demand response within a corresponding program has further shown a variety of reasons that inhibit households from providing demand response when confronted with regular digital energy consumption feedback [58]. We found that it might not only be a reduction in comfort that can hamper the provision of demand response, but also a lack of energy literacy. While the prosumers specifically stated to have shifted their demand into times with more renewable generation, data failed to show this. This discrepancy can potentially be attributed to low knowledge of actual appliance consumption. One recent study highlighted the importance of energy literacy for the response to price signals from electricity markets [51]. Manual demand response with appliances that do not significantly contribute to consumption or irregular demand response that only occurs from time to time will impact the perceived demand response but will not necessarily show in the data. In other words, there might be a discrepancy between perceived demand response and actual demand response, which is problematic for balancing the grid through ECs. Beyond the prosumers, several consumers stated that they did not purposefully shift their demand in response to the price changes. This is in line with results on self-reported demand response from another field study [58]. Therefore, even minor evidence that some intraday demand response occurred could be called into question. While Woerner et al. [73] stated that they expect LEMs within ECs to contribute to system flexibility in terms of demand response, the authors arrived at this conclusion solely because consumers stated they would shift demand into more sunny hours but did not validate these statements empirically. However, the prosumers in our study made similar claims, which could not be substantiated. Furthermore, similar to our results, Woerner et al. [73] found that large portions of locally generated sustainable energy was sold to the grid because users did not shift demand to these cheaper hours arguing that monetary incentives might have been too small. This also implies the low potential of manual demand response. However, the underlying wholesale price difference reflected by the price difference in the LAMP was large. These results are in line with other recent reports of a rather low potential for manual demand response [58]. As argued in [58], the observed shortfall might be remedied through corresponding automation technology that would allow for automated demand response once larger electrical appliances are connected such as heat pumps, electric vehicles and stationary residential storage that can react quickly and considerably to price incentives. Such automation has been reported to be positively viewed by households [58]. The communication of price signals and the corresponding demand response does then happen automatically and in the background to ensure a more reliable demand response. It is important to avoid so-called avalanche effects, where a mass response of many appliances to a signal could turn a demand shortage into a supply shortage [28]. However, this type of EC with an LEM with large-scale automated demand response should be designed differently. For instance, the user interface of the market would have to include features that explain local control actions to participants. It is also the subject of further research how constraints and bids would be set in such a design.

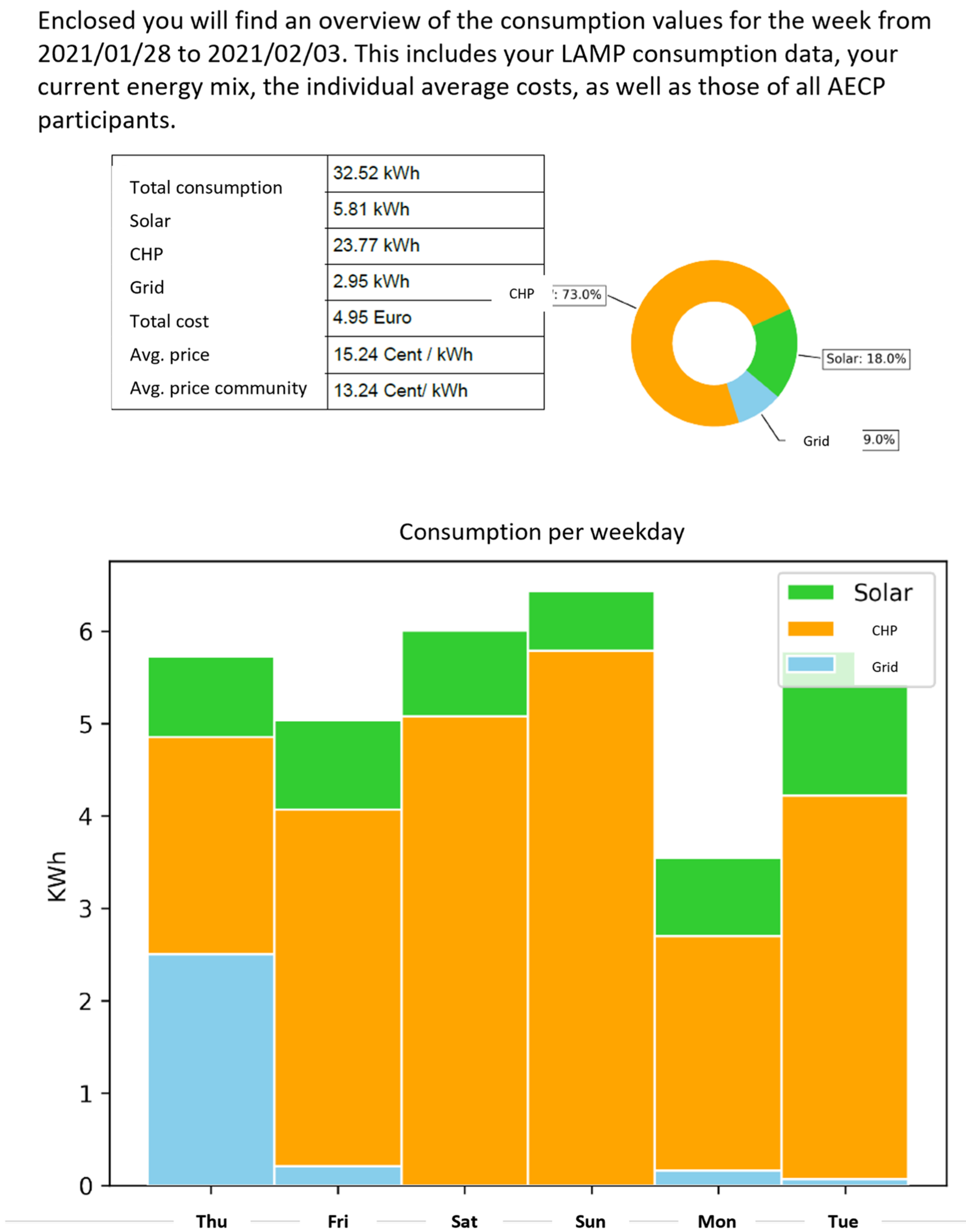
Participant interaction with ECs The user interaction with the provided digital interface underlines a strong desire of our participants for a more granular control of electricity consumption and costs. This result is in line with [2]. The most praised feature of the digitally enabled EC was not the LEM that allowed for cost savings or the opportunity to consume locally generated electricity but the regular feedback on consumption and costs. In essence, the participants were happy about the insights into their behavior to better understand their consumption patterns. This is meaningful because such digital capabilities will, in the long-term, increase energy literacy. Participants will better understand the consequences of their consumption. This is also in line with the finding that the participation in ECs is mostly driven by normative factors such as the desire to save energy or consume renewable energy, whereas financial considerations are less important [60]. Our case seems to confirm this finding and the results further describe a possible corresponding value added by ECs. At the same time, participants strongly criticized the market mechanism. They felt that it was not transparent, which was mostly attributed to a lack of direct market feedback: when participants changed their bids, this did not necessarily change their market results. This is generally the case for markets with a single clearing price. Other researchers have used different mechanisms that are more responsive to bid changes of individuals but are therefore also more prone to market gaming (e.g., [73]). It remains debatable whether a more engaging mechanism that induces a more game-like experience is preferential over an information-efficient and incentive-compatible but less responsive mechanism. Participants also stated they were only willing to spend little time on understanding the mechanism, as power consumption is only a small part of their overall household budget. These results are again indicative of preferences for simpler designs within the participant group. A market mechanism that is poorly understood and causes frustration does not yield effective results. Interestingly, Woerner et al. [73] concluded that participants improved in their interaction with the market over time, which we cannot confirm. However, this conclusion in [73] is based on users lowering their bids over time, which could be a reaction to the reference price or repeated market interaction. Interestingly, lowering bids is not the dominant strategy in the market design of Quartierstrom [73]. The bidding behavior of participants and their interview statements show that once participants were satisfied with their general results, they do not interact with the market anymore. This resonates with previous insights in [73] and motivates further research into well-designed tariff menus to guide behavior on ECs. Klaasen et al. [26] have similarly argued that easier tariff designs are more likely to lead to demand response. Additionally, Parrish et al. [48] pointed out that predictable incentives might increase demand response. We acknowledge that our market design is only one out of many possible designs, and that it does not allow a conclusive judgement on the efficacy of all market mechanisms in LEMs. Our chosen design is a combination of two central pay-as-cleared mechanisms performed in the order as determined by the Borda count. Other mechanisms proposed in the literature are similarly complicated (e.g., [77] incorporate further parameters in the bidding format such as quality, [68] optimize the market, taking grid constraints into account, [10] formulate additional flexibility contracts and [73] set the price based on both the bidding and asking price of matched participants). The complexity of market mechanisms is of course subjective and it is therefore up for debate and further research to assess whether other market mechanisms or tariff designs are better evaluated by EC participants. However, the results encourage research into some form of tariffs that communicate economic signals to households where appliances react to these prices automatically or that enable households to rely on heuristics in their response to the signal. In that same line of argument, Parrish et al. [48] found that enabling technologies (i.e., automation) that do not reduce trust or perceived control could further enhance demand response. Corresponding tariffs can, in principle, be based on preferences in the sense that a tariff menu is offered from which EC participants can choose. However, it is necessary to balance complexity with efficiency as our empirical case study seems to indicate.

Automated bidding This argument can even be strengthened based on our experimentation with automated agents. As the results show, a decent strategy was to simply bid low into the market on this LEM. Whenever supply exceeded demand, the lowest bid determineed the price. Therefore, if one participant decideed to constantly bid low, prices would always be low in times of excess supply. On the contrary, if demand exceeded supply, it is the equilibrium strategy to bid very closely to the upper limit (given that this upper limit is below the overall willingness-to-pay, which in the case of power consumption should mostly be the case), which is the grid price (in the absence of a willingness to pay a premium). Since in the LAMP, the PV generation is usually high compared to the demand of only 11 participants in the EC, it often exceeds demand and always bidding low is a good strategy.[3] Nevertheless, as we have shown, the agent was still able to further reduce the costs for the represented participant. Given that these agents can be implemented with virtually zero marginal costs, all participants are incentivized to let such agents do their bidding for them. To assess the results of such situations, where only agents bid against each other, we simulated this competition using empirical data from the LAMP. The results show what could be expected. In times of excess supply, prices almost always dropped to the lower bound, the feed-in tariff for PV generation. And in times of excess demand, prices almost always rose to the reference grid price, the upper bound. Cases when this did not occur were caused by faulty agent forecasts, which would of course also occur in practice. These results show that the theoretical market equilibria (priced at the lower bound in case of excess supply, price at the upper bound in case of excess demand) are reached when using autonomous bidding agents. One could argue that this is only true in the absence of storage. But this is only the case if the cyclical costs of storage range between the feed-in tariff (or the marginal cost of renewable generation in the absence of a feed-in tariff, i.e., zero) and the reference grid price. Even then, this would simply introduce another equilibrium price on the spectrum. This further motivates additional research into dynamic tariff menus. A few propositions for such a tariff design and constraints that need to be considered are presented in [24]. It should be noted that at the time of the case study, the AI-based algorithms for the agent were not subject to regulation. It is an interesting area of research to evaluate in what way the EU AI Act influences similar architectures.

[3] Optimizing households would, however, try to bid somewhat higher to remain in the market in the dusk and dawn hours when, regularly, demand would exceed supply.

Conclusions

This paper presents an empirical case study on a digitally enabled energy community that features a local energy market. We evaluate assumptions on energy communities that have previously not been thoroughly investigated in the field. To the best of our knowledge, this is the longest reported field observation of an energy community to-date. We implemented an energy community that was operational for more than two years. Specifically, we present data from 13 months of active P2P trading phases and a subsequent 5-month period that saw the implementation of an automated trading agent. The long duration of this case study allows for a better observation of changing behavior over time. This is also the first empirical study to implement a computational trading agent that interacts with human market participants. We use a mixed-method approach and pair quantitative results from the long-term interactions of participants with the energy community with findings from semi-structured interviews with said participants after the project. Our insights support the further development of digital energy communities that feature local energy markets. Our results indicate that the chosen design of the local energy market reduced an existing willingness to pay a price premium for locally generated renewable energy. Furthermore, manual demand response cannot necessarily be expected. Even a price incentive of 100 Euros per MWh was insufficient to trigger relevant manual behavior change of participants in our study. Additionally, a low energy literacy seems to have inhibited willing participants from a relevant contribution to demand response. Study participants used digital features provided to the energy community to increase their energy literacy by trying to better control their costs and consumption as well as the consumption of individual appliances. We also find that the market mechanism introduced certain complexity that participants were not necessarily willing to accept. This requires further empirical research into


Enclosed you will find an overview of the consumption values for the week from 2021/01/28 to 2021/02/03. This includes your LAMP consumption data, your current energy mix, the individual average costs, as well as those of all AECP participants.

Total consumption	32.52 kWh
Solar	5.81 kWh
CHP	23.77 kWh
Grid	2.95 kWh
Total cost	4.95 Euro
Avg. price	15.24 Cent / kWh
Avg. price community	13.24 Cent/ kWh

Fig. 7 Exemplary report

the adequacy of tariff menus that balance perceived complexity with perceived control. The results suggest that willing participants of energy communities are interested in engaging with their energy consumption and local energy generation. This highlights the social and educational value of energy communities. Finally, we implemented an automated trading agent that participated in the market with otherwise human traders representing one participant. We find that such an agent can improve individual market results but that replacing all participants with automated agents leads to game-theoretically optimal market results that resemble a dynamic tariff.

Limitations Similar to [73], our sample size does not allow for statistical significance. We address this challenge by enriching our results with findings from semi-structured interviews. However, our results confirm various findings from previous work [73] in another country with a different underlying sample. Furthermore, we describe various theoretical foundations to which we generalize with this case according to [76]. However, some aspects coincide between the two studies and remain a concern of potential bias. First, participants self-selected, which clearly leads to a selection bias in the considered samples [7]. Second, the samples share certain properties. Both samples are German speaking communities with somewhat shared cultural traditions and both samples come from rather well-situated neighborhoods. However, it is unclear in what kind of neighborhoods ECs would actually strive. Soeiro et al. [60] argued that the decision to participate in a EC is mostly driven by normative factors, which could in turn imply that the sample neighborhoods might actually be representative of future EC communities. Contrary to this, Caramizaru et al. [14] argued that ECs should be established to benefit the full societal spectrum. Moreover, it is difficult to establish benchmarks to compare against within field studies, and our results regarding demand response need to be considered with care. However, consumer statements not to have reacted to price signals and that the benchmark results were consistent for all prosumers give some credence to our findings.

Future research Larger and more diverse case studies or quantitative research on energy communities is needed to confirm the results of our case. To further improve energy communities and their social and educational advantages, researchers can contribute and evaluate further mechanisms and designs for energy communities. For instance, energy communities could be equipped with control technology that can automatically react to external signals to ensure a more reliable demand response. This recommendation is in line with [58] and can be built on low-complexity allocation mechanisms or tariff solutions for ECs with technology that allows for automated demand response such as heat pumps, electric vehicles, and stationary storage. More research is needed on whether consumers would accept such automation technology and what it would do to perceived complexity. Such technology offers the possibility to involve aggregators that market the resulting community flexibility. Corresponding designs open various avenues for further research particularly in terms of the development of business models for energy communities. Finally, how to effectively engage households in EC initiatives is an interesting avenue for future research. This way, ECs might add technical and economic advantages to their social innovation potential and become a pillar of a just and sustainable energy transition in the near future.

Appendix: Interview protocol

Introduction

Thank you for agreeing to this interview. We greatly value your personal impressions and opinions about the LAMP project. By the end of the year, LAMP will transition into the subsequent project 'Smart Grid as a Service'. This means LAMP itself will be a part of a research project wherein several communities like this will be built. Our primary aim is to determine how to easily and efficiently set up such communities in different municipalities. The project is funded by the Federal Ministry of Education and Research and is in collaboration with ESW and other municipal utilities. The experiences gathered in LAMP to-date, both in terms of technical setup and feedback received, assist us in the new project. This is why we are interviewing all participants to gain a comprehensive overview of the impressions of the LAMP project and what we can improve in the future. The interview will take approximately 45 min, and I will ask questions on various topics, such as the market mechanism, trading phase, and the app. Do you have any questions before we begin?

General information

a. Demographics
   - Age, Type of House, Household Size

b. Introduction to LAMP

   i. What specifically piqued your interest in the LAMP project?
   ii. Why did you decide to participate in LAMP?
   iii. Do you have an understanding of LAMP's objectives?
   iv. Have you discussed the LAMP project within your household or neighborhood?
   v. Would you recommend LAMP to friends, neighbors, or relatives?
   vi. How important is it for you to source electricity from local, potentially green sources?

c. Basic participant classification

   i. Were you aware of your monthly/annual electricity costs before joining LAMP?
   ii. What new insights about your electricity costs did LAMP provide?
   iii. Were you aware of your energy consumption (kWh) annually/monthly/daily before joining LAMP?
   iv. Has LAMP changed your consumption behavior?

LAMP pricing and origin of electricity

a. Perception of pricing (general)

   i. How did you perceive the price formation in LAMP?

b. Perception of pricing (community/ source of electricity)

   i. How fair do you find LAMP's pricing?
   ii. How do you rate LAMP's uniform price compared to individual pricing for each participant?
   iii. How important is it for you to know the quantity and local source (or neighbors) from which you get your electricity?

c. Perception of pricing (time-based)

   i. Did you monitor the market prices and did the price and its evolution lead you to adjust your bids?
   ii. Before LAMP, you had a fixed rate with your energy supplier. How do you evaluate such a fixed rate compared to a LAMP price that can change every 15 min?
   iii. What duration (time during which the price remains unchanged) do you think is appropriate?

d. Understanding of pricing

   i. Were you able to understand the mechanics of price formation?

Trading phases and reports

a. Perception (general)

   i. How did you perceive the trading phases in LAMP?
   ii. What was the value of the weekly reports for you?

b. Perception and behavior in trading phases

   i. Did you adjust your bid settings or electricity consumption behavior based on the information provided in the reports during one or more trading phases?

c. Understanding of trading phases and reports

   i. Were you able to understand the content and significance of the reports provided during the trading phases?
   ii. What additional information or aspects would you have liked to see in these reports?

LAMP app experience

a. Overall experience

   i. How would you evaluate your overall experience with the LAMP app?
   ii. Were you able to understand the various features of the app?

b. Functions and features

   i. Which functionalities or features of the app did you find most useful?
   ii. Which functionalities or features do you think were missing or could be improved?

c. UI/UX feedback

   i. Was the app's design and user interface intuitive and user-friendly?
   ii. What specific improvements would you recommend for the app's design?

d. Overall feedback

   i. Would you continue to use the LAMP app or a similar app in the future?
   ii. What additional features or aspects would make you more inclined to use such an app regularly?

Feedback and conclusion

a. Suggestions and recommendations

   - Are there any features, aspects, or elements that you would like to see in future similar projects?
   - Do you have any recommendations on how to improve the overall participant experience?

b. General feedback

   - What did you like most about participating in the LAMP project?

- What did you like the least?

c. Closing words
  - Thank you for your valuable input. Your feedback is essential in guiding future projects. If you have any further comments or suggestions, please feel free to share.

Acknowledgements
We thank the anonymous reviewers and editors for their constructive feedback and engagement with the paper. It greatly improved throughout the reviewing process. Furthermore, we thank David Umbach for copy-editing the paper.

Author contributions
PS authored and edited the main manuscript, analyzed and interpreted data, and developed the study design and treatments. BR developed the methods, collected, analyzed and interpreted data, designed the figures presented in the manuscript, and programmed the intelligent trading agent.

Funding
Open Access funding enabled and organized by Projekt DEAL. This research received no external funding.

Data availability
The authors can provide all data upon request.

Declarations

Ethics approval and consent to participate
This research adhered to all aspects of the Declaration of Helsinki. Participants gave informed written consent prior to participation and were able to withdraw at any time without penalty.

Competing interests
There are no competing interest to disclose, financial or otherwise.

Received: 29 August 2023 Accepted: 8 January 2025
Published online: 22 January 2025

References

1. (2019) Abstracts from the 8th dach+ conference on energy informatics. Energy Inf. 2(2):31. https://doi.org/10.1186/s42162-019-0098-7
2. Ableitner L, Tiefenbeck V, Meeuw A et al (2020) User behavior in a real-world peer-to-peer electricity market. Appl Energ 270:115061
3. Agarwal R, Garg M, Tejaswini D, et al (2023) A review of residential energy feedback studies. Energ Buildings p 113071
4. Audenhove LV, Donders K (2019) Talking to people iii: Expert interviews and elite interviews. In: The Palgrave handbook of methods for media policy research. Springer, p 179–197
5. Azarova V, Cohen J, Friedl C et al (2019) Designing local renewable energy communities to increase social acceptance: evidence from a choice experiment in austria, germany, italy, and switzerland. Energ Pol 132:1176–1183
6. Ban NC, Mills M, Tam J et al (2013) A social-ecological approach to conservation planning: embedding social considerations. Front Ecol Environ 11(4):194–202
7. Belot M, James J (2014) A new perspective on the issue of selection bias in randomized controlled field experiments. Econ Lett 124(3):326–328
8. Borchers AM, Duke JM, Parsons GR (2007) Does willingness to pay for green energy differ by source? Energ Pol 35(6):3327–3334
9. Bose S, Kremers E, Mengelkamp EM et al (2021) Reinforcement learning in local energy markets. Energy Inf 4(1):7
10. Bremdal BA, Olivella-Rosell P, Rajasekharan J et al (2017) Creating a local energy market. CIRED-Open Access Proc J 1:2649–2652
11. Brummer V (2018) Community energy-benefits and barriers: a comparative literature review of community energy in the UK, Germany and the USA, the benefits it provides for society and the barriers it faces. Renew Sust Energ Rev 94:187–196
12. Budiman I (2018) Enabling community participation for social innovation in the energy sector. Ind J Energy 1(2):21–31
13. Capellán-Pérez I, Campos-Celador Á, Terés-Zubiaga J (2018) Renewable energy cooperatives as an instrument towards the energy transition in Spain. Energ Pol 123:215–229
14. Caramizaru A, Uihlein A, et al (2020) Energy communities: an overview of energy and social innovation, vol 30083. Publications Office of the European Union Luxembourg
15. Chen T, Su W (2018) Local energy trading behavior modeling with deep reinforcement learning. IEEE Access 6:62806–62814
16. Cornélusse B, Savelli I, Paoletti S et al (2019) A community microgrid architecture with an internal local market. Appl Energ 242:547–560
17. Desley V, Laurie B, Peter M (2013) The effectiveness of energy feedback for conservation and peak demand: a literature review. Open J Energy Efficiency 2013
18. Dudjak V, Neves D, Alskaif T et al (2021) Impact of local energy markets integration in power systems layer: a comprehensive review. Appl Energ 301:117434
19. Emerson P (2013) The original borda count and partial voting. Soc Choice Welfare 40:353–358
20. Falk A, Szech N (2013) Morals and markets. Science 340(6133):707–711
21. Furnham A, Boo HC (2011) A literature review of the anchoring effect. J Socio Econ 40(1):35–42
22. Gholami R, Emrouznejad A, Alsnour Y, et al (2021) The impact of smart meter installation on attitude change towards energy consumption behavior among northern Ireland households. In: Research Anthology on Clean Energy Management and Solutions. IGI Global, p 925–943
23. Gui EM, MacGill I (2018) Typology of future clean energy communities: an exploratory structure, opportunities, and challenges. Energy Res Soc Sci 35:94–107
24. Henni S, Staudt P, Weinhardt C (2021) A sharing economy for residential communities with pv-coupled battery storage: Benefits, pricing and participant matching. Appl Energ 301:117351
25. Kaenzig J, Heinzle SL, Wüstenhagen R (2013) Whatever the customer wants, the customer gets? Exploring the gap between consumer preferences and default electricity products in germany. Energ Pol 53:311–322
26. Klaassen EA, Kobus CB, Frunt J et al (2016) Responsiveness of residential electricity demand to dynamic tariffs: experiences from a large field test in the netherlands. Appl Energ 183:1065–1074
27. Koirala BP, Koliou E, Friege J et al (2016) Energetic communities for community energy: a review of key issues and trends shaping integrated community energy systems. Renew Sust Energ Rev 56:722–744
28. Kühnbach M, Stute J, Klingler AL (2021) Impacts of avalanche effects of price-optimized electric vehicle charging-does demand response make it worse? Energy Strateg Rev 34:100608
29. Lennon B, Dunphy NP, Sanvicente E (2019) Community acceptability and the energy transition: a citizens' perspective. Energ Sust Soc 9(1):1–18
30. Leonhardt R, Noble B, Poelzer G et al (2022) Advancing local energy transitions: a global review of government instruments supporting community energy. Energy Res Soc Sci 83:102350
31. Lezama F, Soares J, Hernandez-Leal P et al (2018) Local energy markets: paving the path toward fully transactive energy systems. IEEE T Power Syst 34(5):4081–4088
32. Liu Y, Wu L, Li J (2019) Peer-to-peer (p2p) electricity trading in distribution systems of the future. Electricity J 32(4):2–6
33. Lombardo A, Parrino S, Peruzzi G et al (2021) Lorawan versus nb-iot: transmission performance analysis within critical environments. IEEE Int Things 9(2):1068–1081
34. Lowitzsch J, Hoicka CE, van Tulder FJ (2020) Renewable energy communities under the 2019 European clean energy package-governance model for the energy clusters of the future? Renew Sust Energ Rev 122:109489
35. McCalley L, Midden CJ (2002) Energy conservation through product-integrated feedback: the roles of goal-setting and social orientation. J Econ Psychol 23(5):589–603

36. Mengelkamp E, Staudt P, Garttner J, et al (2017) Trading on local energy markets: A comparison of market designs and bidding strategies. In: 2017 14th International Conference on the European Energy Market (EEM), IEEE, pp 1–6
37. Mengelkamp E, Gärttner J, Rock K et al (2018) Designing microgrid energy markets: a case study: the Brooklyn microgrid. Appl Energ 210:870–880
38. Mengelkamp E, Staudt P, Gärttner J, et al (2018b) Quantifying factors for participation in local electricity markets. In: 2018 15th International Conference on the European Energy Market (EEM), IEEE, pp 1–5
39. Mengelkamp E, Richter B, Maier H, et al (2023) Value and regulation of local electricity markets. Abstracts from the 8th DACH+ Conference on Energy Informatics Energy Inform 2 (Suppl 2), 31
40. Morstyn T, Farrell N, Darby SJ et al (2018) Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants. Nature Energy 3(2):94–101
41. Müller SC, Welpe IM (2018) Sharing electricity storage at the community level: an empirical analysis of potential business models and barriers. Energ Pol 118:492–503
42. Oberst CA, Schmitz H, Madlener R (2019) Are prosumer households that much different? evidence from stated residential energy consumption in Germany. Ecol Econ 158:101–115
43. Olivares DE, Mehrizi-Sani A, Etemadi AH et al (2014) Trends in microgrid control. IEEE T Smart Grid 5(4):1905–1919
44. OShaughnessy EJ, Heeter JS, Gattaciecca J, et al (2019) Community choice aggregation: challenges, opportunities, and impacts on renewable energy markets. Tech. rep
45. Palm J, Eidenskog M, Luthander R (2018) Sufficiency, change, and flexibility: critically examining the energy consumption profiles of solar pv prosumers in sweden. Energy Res Soc Sci 39:12–18
46. Parag Y, Sovacool BK (2016) Electricity market design for the prosumer era. Nat Energ 1(4):1–6
47. Parliament E (2019) Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending directive 2012/27/eu. Official J Eur Union 50:125–199
48. Parrish B, Heptonstall P, Gross R et al (2020) A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response. Energ Pol 138:111221
49. Pouttu A, Haapola J, Ahokangas P, et al (2017) P2p model for distributed energy trading, grid control and ict for local smart grids. In: 2017 European Conference on Networks and Communications (EuCNC), IEEE, pp 1–6
50. Reijnders VM, van der Laan MD, Dijkstra R (2020) Energy communities: a Dutch case study. In: Behind and beyond the meter. Elsevier, p 137–155
51. Reis IF, Lopes MA, Antunes CH (2021) Energy literacy: an overlooked concept to end users' adoption of time-differentiated tariffs. Energ Effic 14(4):1–28
52. Richter B, Mengelkamp E, Weinhardt C (2019) Vote for your energy: a market mechanism for local energy markets based on the consumers' preferences. In: 2019 16th International Conference on the European Energy Market (EEM), IEEE, pp 1–6
53. Richter B, Golla A, Welle K et al (2021) Local energy markets-an it-architecture design. Energy Inf 4(2):1–21
54. Richter B, Staudt P, Weinhardt C (2022) Citizen energy communities-insights into long-term participant behavior from a field study. Tech. rep
55. Romero-Rubio C, de Andrés Díaz JR (2015) Sustainable energy communities: a study contrasting Spain and Germany. Energ Pol 85:397–409
56. Roth T, Utz M, Baumgarte F et al (2022) Electricity powered by blockchain: a review with a European perspective. Appl Energ 325:119799
57. Schmitt C, Schumann K, Kollenda K et al (2022) How will local energy markets influence the pan-European day-ahead market and transmission systems? a case study for local markets in France and Germany. Appl Energ 325:119913
58. Schrammel J, Diamond LM, Fröhlich P et al (2023) Influencing residential electricity consumption with tailored messages: long-term usage patterns and effects on user experience. Energ Sust Soc 13(1):15
59. Schwartz T, Denef S, Stevens G, et al (2013) Cultivating energy literacy: results from a longitudinal living lab study of a home energy management system. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp 1193–1202
60. Soeiro S, Dias MF (2020) Renewable energy community and the European energy market: main motivations. Heliyon 6(7):e04511
61. Sokołowski MM (2020) Renewable and citizen energy communities in the European union: how (not) to regulate community energy in national laws and policies. J Energy Nat Res Law 38(3):289–304
62. Sousa T, Soares T, Pinson P et al (2019) Peer-to-peer and community-based markets: a comprehensive review. Renew Sust Energ Rev 104:367–378
63. Stadler M, Cardoso G, Mashayekh S et al (2016) Value streams in microgrids: a literature review. Appl Energ 162:980–989
64. Tabi A, Hille SL, Wüstenhagen R (2014) What makes people seal the green power deal?-customer segmentation based on choice experiment in Germany. Ecol Econ 107:206–215
65. Tarpani E, Piselli C, Fabiani C et al (2022) Energy communities implementation in the European union: case studies from pioneer and laggard countries. Sustainability-Basel 14(19):12528
66. Teotia F, Bhakar R (2016) Local energy markets: Concept, design and operation. In: 2016 National Power Systems Conference (NPSC), IEEE, pp 1–6
67. Torbaghan SS, Blaauwbroek N, Nguyen P, et al (2016) Local market framework for exploiting flexibility from the end users. In: 2016 13th International Conference on the European Energy Market (EEM), IEEE, pp 1–6
68. Vasconcelos M, Cramer W, Schmitt C, et al (2019) The pebbles project–enabling blockchain based transactive energy trading of energy & flexibility within a regional market. Tech. rep
69. Wagner J, Namockel N, Gruber K (2021) Ökonomische bewertung des nutzens lokaler koordinationsmechanismen in der stromversorgung: Report by the institute of energy economics at the university of cologne (ewi) on behalf of siemens ag and allgäuer überlandwerk gmbh. Tech. rep
70. Walker G, Devine-Wright P (2008) Community renewable energy: what should it mean? Energ Pol 36(2):497–500
71. Warneryd M, Håkansson M, Karltorp K (2020) Unpacking the complexity of community microgrids: a review of institutions' roles for development of microgrids. Renew Sust Energ Rev 121:109690
72. Weinhardt C, Mengelkamp E, Cramer W, et al (2019) How far along are local energy markets in the dach+ region? a comparative market engineering approach. In: Proceedings of the tenth ACM international conference on future energy systems, pp 544–549
73. Wörner A, Tiefenbeck V, Wortmann F, et al (2022) Bidding on a peer-to-peer energy market: An exploratory field study. Inform Syst Res
74. Wörner AM, Ableitner L, Meeuw A, et al (2019) Peer-to-peer energy trading in the real world: Market design and evaluation of the user value proposition. ICIS 2019 Proceedings 2:1221
75. Wu FF, Varaiya PP, Hui RS (2015) Smart grids with intelligent periphery: an architecture for the energy internet. Engineering-London 1(4):436–446
76. Yin RK (2009) Case study research: Design and methods, vol 5. sage
77. Zade M, Lumpp SD, Tzscheutschler P et al (2022) Satisfying user preferences in community-based local energy markets-auction-based clearing approaches. Appl Energ 306:118004
78. Zhang C, Wu J, Zhou Y et al (2018) Peer-to-peer energy trading in a microgrid. Appl Energ 220:1–12
79. Zhang M, Eliassen F, Taherkordi A, et al (2019) Energy trading with demand response in a community-based p2p energy market. In: 2019 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), IEEE, pp 1–6
80. Zwickl-Bernhard S, Auer H (2021) Citizen participation in low-carbon energy systems: energy communities and its impact on the electricity demand on neighborhood and national level. Energies 14(2):305

Publisher's Note