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User behavior in a real-world peer-to-peer electricity market

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HIGHLIGHTS

- Real-word deployment and evaluation of a P2P energy market with 37 households.
- Relatively stable use of the web application.
- Heterogeneous user behavior and stated preferences indicate three user clusters.
- Indications for increased load-shifting due to salience of renewable energy.

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ABSTRACT

Peer-to-peer (P2P) energy markets are a widely discussed approach toward a sustainable energy supply that allows private owners of distributed energy resources (e.g., solar panels) and consuming households to trade energy directly without intermediaries. P2P energy markets are expected to contribute to a green, local, and fair energy system in the future. The approach implies a paradigm shift regarding the role of citizens who evolve from passive consumers into active market participants. While first existing research primarily focused on the technical feasibility of such scenarios, end users and their role in P2P markets have received little attention. The present article studies the behavior of 35 households and two commercial entities in Switzerland's first real-world P2P energy market. In this unique real-world setting, based on a mixed methods approach, we developed and deployed a web application and empirically studied interaction, acceptance, and participation in electricity pricing in this P2P energy market, using data from system logs, surveys, and interviews. The findings are threefold. First, the P2P energy market was well received among its users, indicated by comparably high and stable usage activity of the web application throughout the study (4.5 months). Second, users in the sample are heterogeneous; based on their engagement with the web application and their stated preferences, they can be categorized into those who want to actively set prices (30%); those who prefer automated prices determined by an information system (35%); and non-users/non-respondents to surveys (35%). Third, an analysis of interviews with nine households suggests that P2P energy markets may increase the salience of renewable energies and may promote load-shifting activities. Thus, the article provides empirical insights about the user behavior of households and their future role in decentralized energy scenarios.

1. Introduction

With rising standards of living, societies all around the globe need secure energy supplies at affordable prices and with the least possible negative impact on the natural environment [1]. Based on the Paris Agreement, many countries have introduced strict climate targets for the mitigation of climate change [2,3]. These directives are heavily dependent upon a shift from a few large power plants fueled by fossil fuels toward a distributed energy landscape based on renewable energies. These developments imply a new role of citizens, who will “take ownership of the energy transition, benefit from new technologies to reduce their bills, and participate actively in the market” [3]. With fast technological progress at continuously falling installation costs [4,5], distributed energy resources (DER) have become economically attractive for private households. By installing photovoltaic systems on their roofs, households are able to generate and (partly) self-consume their

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own electricity. This has caused a paradigm shift from passive consumers to active prosumers [6] who not only consume electricity, but also produce it. As a result of these developments, more and more individuals no longer consider electricity to be a given commodity; instead, they tend to value its environmentally friendly production as well as the fact that they can be (partially) self-sufficient (i.e., being independent from the electricity provider and its tariffs for buying electricity) [7–9]. These preferences regarding electricity supply apply not only to prosumers, but also to an increasing number of consumers, and are similar to current phenomena witnessed in other industries, where consumers increasingly state an appreciation for green, local, and fair products (e.g., biological and regional food production [10], fair trade labels [11], or ethical clothing [12]).

A particularity in the electricity sector is that at the grid level, supply and demand need to always match. At the prosumer level, the timing of solar production typically only coincides with the household's demand to a limited extent. Today, prosumers in most countries essentially have two options regarding their surplus solar production: They can either inject it into the grid for a monetary compensation ("feed-in tariff") or they can store it in a battery storage system for use at a later point in time. However, feed-in tariffs in most regions decrease as governments cut back on subsidies, making the profitability of investments uncertain [5,13]. Battery storage systems, on the other hand, are still expensive and not profitable yet for the vast majority of stand-alone households [14]. As a result, peer-to-peer (P2P) energy trading in microgrids is of particular interest to researchers and practitioners alike as a potential future energy scenario.

The concept of a P2P energy market is built on the general idea of the sharing economy, "a socioeconomic ecosystem that commonly uses information technology to connect different stakeholders – individuals, companies, governments – to share, or access different products and services and to enable collaborative consumption" [15]. Both scholars and practitioners have drawn parallels to sharing economy applications in other sectors, referring to P2P energy trading as the Airbnb or Uber of the energy sector [16,17]. In a P2P energy market, prosumers can sell their surplus electricity to neighbors who do not own a PV system themselves, or whose current demand exceeds their production. From a technical point of view, information technology is more and more capable of managing such decentralized energy systems in an automated manner (e.g., energy allocation and financial settlement using blockchain technology) [18]. From a coordination and financial point of view, aggregating several actors with heterogeneous load profiles in a microgrid increases the share of electricity that is consumed and produced locally, compared to stand-alone households, which individually optimize their self-consumption or self-production [19,20]. Simulation results indicate that coordinating several actors at the microgrid level makes investments in PV and battery storage systems more economically attractive [19,20]. Consequently, P2P energy markets might satisfy newly evolved user preferences on electricity [8], reduce the amortization uncertainty of DER investments [8], and keep profits within the local region [18]. All of this could motivate households further to invest in and adopt DERs, which is important with regard to the energy transition towards sustainability, and also addresses the increasingly strategic role of electricity as an energy source with the ongoing electrification of the mobility and heating sectors (e.g., electric vehicles, heat pumps) [21,22].

Given the fact that P2P energy markets consist of small-scale energy producers who contribute to the local community with their DERs, the success of P2P energy hinges on individuals' willingness to participate in such markets [23]. Yet, while many individuals state that they value such P2P concepts, P2P applications (also in other sectors) are prone to an attitude-behavior gap relating to the fact that individuals' stated positive attitudes do not translate in them taking the steps to actually adopt these systems [24]. In that regard, Sousa et al. [25] consider lack of user engagement as one of the main threats to the concept of P2P energy markets. Likewise, Mengelkamp et al. [18] argue that the "socio-economic perspective of microgrid energy markets is mostly neglected in current research". Hence, recent literature has called for studying individually evolving preferences, new user needs, and new incentive mechanisms [7,8,18]. Existing literature on P2P energy trading mainly provides concepts [8,17] or simulation-based analyses [26,27] on the technical feasibility of P2P energy. While all these aspects contribute highly relevant aspects for assessing the potential of P2P energy markets, research that focuses on the user is still scarce, and the role that households could realistically assume in P2P energy trading is still an open question. First studies in the topic area report that 79% of 830 European survey participants are in favor of joining P2P energy markets [28] and that 77% of participants of an online experiment actively engage in P2P trading decisions [29]. While these hypothetical findings are certainly promising regarding the potential uptake of P2P energy markets by prospective users, concrete case studies and pilot-tests of real-world applications are needed to empirically study user behavior in P2P energy markets. The necessity to do so grows in importance in the light of other products that have been introduced in the energy sector. The majority of them have overwhelmed most users with their level of technical complexity and they have failed to successfully engage users over a longer period, resulting in a non-materialization of the intended efficiency targets [30–32]. P2P energy markets represent an even more complex case, as their members need to grasp at least basic technical aspects of DER generation (e.g., the influence of weather, production times during the day, optimization of self-consumption) and economic relationships (e.g., balance of supply and demand, electricity prices, network tariffs/transaction costs) to develop a basic understanding of the market dynamics. To incentivize further DER adoption, P2P energy markets therefore hinge on whether the user interface (UI) of these markets successfully meets actual user needs.

This article sheds light on the role households could assume in P2P energy markets by empirically studying user needs, acceptance, and interaction in a real-world application of a P2P energy market. To that end, we developed and implemented a P2P energy market consisting of 35 households and two commercial entities in a Swiss neighborhood. The system comprises a total of 27 photovoltaic systems and 8 energy storage systems. In this unique real-world setting, we investigate how participants interact with the UI of our P2P energy market, which granted participants access to their own electricity consumption data (and in the case of prosumers, also their production data). Furthermore, on the UI, participants could set and adjust price limits for trading electricity within the community. Each participant's price limits were communicated every 15 min by the smart meters; together with the participant's consumption (and production) data, the price limits were processed as input data by the market mechanism described in section 4. Thus, these price limits set by the participants were consequential for their utility bills. Beyond that, as part of the field study, we also tested two different pricing mechanisms and evaluated whether participants wanted to actively participate (or not) in the pricing of locally exchanged electricity. Finally, we conducted qualitative interviews with participants on perceived economic, environmental, technological, infrastructural, and social benefits of the P2P energy market. We structure our analysis based on the sensemaking framework [33,34], which analyzes to what extent individuals notice the market information available, how they interpret that information, and how they take action based on these learnings.

This article is one of the first studies that analyzes participants' role in P2P markets based on empirical data from a real-world setting. The key findings are as follows: First, usage statistics show that study participants frequently interacted with the market UI, which is in contrast to many other studies that have assessed user engagement with products and services in the energy sector. We conclude that individuals in our sample were interested in the market activity of a P2P energy market, which is a first signpost that the more active role of participants and the interactive UI they had access to could help increase the understanding and engagement with energy topics among a broader population. Second, we tested different price-setting mechanisms and provide evidence that future technology should address different user preferences regarding active involvement in P2P energy pricing by allowing for both automation and agency. Third, interviews with the participants suggest that P2P energy markets might increase the perceived presence (saliency) of renewable energies, and that the concept might promote load-shifting activities. While future research needs to evaluate to what extent the results generalize to the broader population and to quantify the impact of P2P markets for instance on load-shifting activities, our study makes a first important step in the process of moving behavioral research on P2P energy markets from survey-based hypothetical scenarios to analyzing behavior and attitudes of actual P2P market participants in the real world.

2. Related work

2.1. Conceptual work on the benefits of P2P energy

Research and industry alike have recently placed high hopes on P2P energy markets as a vehicle for sustainable energy. P2P energy markets hold the promise of an optimized allocation of local supply and demand, which enhances grid resilience, reduces the need to inefficiently transport energy over long distances, and may delay or avoid further investments in costly transmission lines [8]. Critics, however, argue that P2P energy markets are just a billing exercise that does not introduce any change to the physical flow of electricity. Indeed, electrons always have and will continue to take the path of least resistance from producer to consumer as long as there is a physical connection between them.

Yet, P2P energy markets could create economic incentives for households to (re-)invest in DERs. First, and as briefly discussed in the introduction, P2P energy markets may reduce the profitability uncertainty of investments in DERs [8], as they offer an alternative market for prosumers to sell their surplus electricity, aside from injecting the electricity into the grid at a given price defined by the grid operator or regulator. Second, a bottom-up approach for demand-actuated grid usage might reduce grid fees considerably, thus increasing the financial benefit for households [17,25]. These economic advantages, in turn, might incentivize further DER investments [8,18]. On top of that, a P2P energy community might further spur the adoption of battery storage systems, as they might be better integrated with aggregated PV generation from a community than with PV systems from stand-alone households [19,20].

Moreover, P2P energy markets might incentivize a larger share of the population to shift their consumption to production times of DERs. So far, only prosumers have had an economic incentive to shift loads to maximize the overlap of their consumption and their electricity production (to avoid selling their production at low feed-in tariffs, while buying electricity later at considerably higher retail tariffs). Thus, also in the absence of P2P energy markets, prosumers have an incentive to optimize the two performance indicators: self-consumption ratio (i.e., the share of generated electricity that is consumed directly) and self-sufficiency ratio (i.e., the extent to which a household is independent from external energy supplies). Given the heterogeneity of the load profiles of different households [14], and given that many households do not have the possibility to install a PV system (e.g., most tenants do not have access to a roof), P2P energy markets increase the self-consumption ratio and the self-sufficiency ratio on a community level [35,36]. In P2P energy markets with dynamic electricity prices, consumer households also have an economic incentive to engage in load-shifting activities to benefit from lower prices when locally generated electricity is available.

In addition, P2P energy markets may address newly evolving user needs around energy by making DER-generated electricity more prominent (=more visible). P2P energy markets offer increased transparency into the origin of consumed electricity respective of the destination of self-generated electricity, thus emphasizing local aspects of electricity generation. Individuals increasingly express interest in both renewable and local energy [7–9]. Moreover, from a social perspective, P2P energy markets may strengthen the local community in terms of independence, creating community relatedness, and granting both prosumer and consumer households active roles in realizing the energy transition [18,25].

Overall, P2P energy markets could foster a sustainable energy supply and thus “P2P exchange of energy is likely to become a pertinent aspect of decentralized energy scenarios” [7].

2.2. Prototypes and first user studies on P2P energy trading

Despite the fact that P2P energy markets hinge on the participation of consumers and prosumers, evidence on actual user interaction with P2P markets is still extremely scarce. A couple of industry-led projects have deployed real-world P2P energy markets. For instance, the UI of the Brooklyn Microgrid primarily focuses on providing insights into energy data, on defining the maximum total amount of money users are willing to spend on electricity, and on identifying roofs in the neighborhood to further expand the community [37]. In the projects TAL.-MARKT and Vandebron, consumers can choose which small-scale producers they buy electricity from and they can trade certificates [38,39]. Piclo Flex offers a competition map for buyers and sellers of flexibility in the UK [40]. While these commercial projects have rudimentary prototypes of UIs in the field, they do not evaluate user interaction with the system (or at least no results have been made publicly available to date).

Likewise, insights from academic studies with a focus on P2P energy market users are very limited. In that regard, Weinhardt et al. [41] provide an overview of nine ongoing research projects in the D-A-CH region (Germany, Austria, Switzerland), of which most are in the development stage. So far, none of the projects has yet published findings on user behavior with real-world applications of P2P energy markets. Ecker et al. [7] and Hahnel et al. [29] conducted online experiments to study user behavior in hypothetical P2P energy environments. In their first experiment on consumers’ willingness to pay for DER electricity, Ecker et al. [7] tested different value propositions of battery-stored electricity. While the participants in their study highly valued both self-sufficiency[1] and autonomy (being able to control their energy management) in general when adopting batteries, only the self-sufficiency framing increased participants’ willingness to pay for locally generated electricity. In their second experiment, Hahnel et al. [29] examined individuals’ strategies for P2P electricity pricing. Individuals were able to either store surplus electricity in their own battery storage systems or to sell it to their local community. The state of charge of the battery storage system and market prices for electricity were manipulated as independent variables in the experiment; the participants’ choices regarding storing or selling served as the dependent variable. Based on the results, the authors argue that there is no one-size-fits-all solution to address newly evolving user needs around P2P energy markets due to the heterogeneity of potential users. Based on participants’ responses in the hypothetical scenario, Hahnel et al. [29] propose a four-segment classification for members of P2P energy markets: classic consumers (22.6%, no interest in trading); price-focused prosumers (38.9%, sensitive to both price and self-sufficiency); self-sufficiency-focused prosumers (31.6%, highly sensitive to self-sufficiency, relatively insensitive to market price changes); and heuristic prosumers (7.0%, highly insensitive to market prices if their state of charge was between 50% and 80%).

[1] Ecker et al. [7] and Hahnel et al. [29] refer to self-sufficiency with the term autarky; we use the term self-sufficiency in the following as it allows us to reflect stages beyond the merely dichotomous variable autarky (defined as being dependent or independent from external energy supplies).

In contrast to the limited empirical findings on user behavior in P2P energy markets, there is a growing body of literature on individuals' motivations for becoming members of P2P energy communities (partly) based on game theoretical approaches (for an overview please refer to [42]). For instance, Tushar et al. [43] applied the transtheoretical model by Prochaska and DiClemente [44] from motivational psychology and identified five stages for the evolution of individual participation in P2P energy markets: being unaware of such solutions, becoming aware of them, committing to join a P2P energy market, joining, and remaining. The authors argue that in each of these stages, different theories from psychology (e.g., rational-economic model, information model) can be leveraged to encourage households to participate in P2P energy markets. To that end, they built a game-theoretical scheme for P2P trading based on these psychological models and validated it with case studies [43]. In [45] Tushar et al. propose a prosumer-centric coalition formation game, in which prosumers can compare their LEM benefits participating with or without their private battery storage systems. In [46] Tushar et al. design a cooperative Stackelberg game for peak shaving, in which utility companies set high electricity prices during peak demand times incentivizing prosumers to reduce their demand during these timeframes. Reuter and Loock [28] conducted a cross-country survey with 830 Swiss, Norwegian, German, and Spanish individuals, examining the population's readiness for P2P energy markets. 79% of survey respondents indicated being in favor of joining P2P markets and ranked environmental motivation before economic, technological/infrastructural, political/being independent and social/community factors. The authors propose implementing real-world applications of P2P energy markets based on financial compensation. In that context, Ecker et al. [7] argued for designing P2P markets in a way that they allow for individual self-determination; more precisely, they suggest including a feature that enables prosumers to state a price at which they are willing to sell their electricity. In a similar vein, Kirchhoff and Strunz [23] have proposed that motivation for participation goes beyond financial incentives. Their Bangladesh-based case study in a stand-alone microgrid without connection to the national grid reveals value to the user that relates to either the general advantages of electrification (reliable access to electricity, independence from diesel generators) or to the user-friendliness of operation. The latter was also taken up by Koirala et al. [47], who stress the importance of a positive user experience in P2P energy markets and suggest taking user feedback into consideration to improve engagement with these systems. Doing so could further impact the diffusion of P2P energy markets, as satisfied community members might spread the word in their circles.

2.3. Research gap

As the literature and empirical work with a socio-economic perspective on P2P energy markets is still scarce, literature calls for social science approaches that aim at understanding the bigger picture of P2P energy, including consumer and prosumer preferences, their impact on market functioning and dynamics, and potential incentives for users to self-organize into coalitions [8,25].

The present article responds to various research calls by analyzing user behavior in P2P energy markets. To that end, we investigate the role of participating households in P2P energy markets in three dimensions: a) interaction with the market, b) different pricing mechanisms, and c) perceived user benefits.

The first research objective explores how users interact with our P2P energy market in the real world, making use of the sensemaking approach, which explains how individuals deal with unforeseen events or novel information [34,48]. In particular, it proposes three stages and focuses on: a) how individuals pay attention to incoming stimuli ("noticing"), b) which efforts they make to interpret and learn from these stimuli ("understanding"), and c) how they take action based on their learnings ("taking action") [33,34]. A sensemaking example in the energy context is when consumers receive a 24-hour load curve of their electricity use. Assuming that they absorb or notice the information, they may disaggregate particular appliances (e.g., the water heater) from standby loads based on the time of use and characteristic spikes in the profile, contrive concrete actions associated with these spikes, and take action (e.g., shifting consumption to sunny weather when renewables generate electricity).

Applying the three stages to P2P energy markets, we evaluate: a) how users take up the market information, b) how much effort they have to invest to understand the information in a broader context, and c) how they perceive affordances that spur action [33,34]. We thus follow Wood et al. [49], who recently applied the sensemaking framework in an energy context, or more precisely for making sense of energy feedback. As "making sense of the world using information technology has become a ubiquitous activity in the digital era" [48], the concept of "Sensemaking has become an umbrella term for efforts at building intelligent systems […], that will […] enable humans to achieve insights, […], [and] present information in relevant ways and defined in terms of some magically derived model of the human subconscious or its storehouse of tacit knowledge" [50].

Based on the user needs previously identified in a focus group study, we have developed a P2P energy market and deployed it in the real world. The system includes a self-developed UI that allows participants to interact with the system. In a first step, we use login data and analyze user interaction with the UI for the P2P energy market (e.g., retrieving information, setting prices) and empirically investigate:

RQ1 How do individuals interact with a P2P energy market?

As a second research objective, we examine two different roles of the households in P2P energy pricing, one that emphasizes agency (by active participation in the pricing), and the other a more passive role characterized by the convenience of automation (when prices are defined by a third party, e.g., the utility company). Generally, pricing of P2P energy is a delicate question, as the P2P concept does not comprise a central institution that defines a global price for P2P energy; instead, it builds on bilateral negotiation of prices. While the active inclusion of the users in the price formation grants them more autonomy in the market, it also implies extensive effort (time and cognitive resources) for the user, compared to the status quo of fixed prices defined by a utility company or regulator. Thus, we conduct a within-subject experiment that manipulates the ability of participants to set prices (yes/no) as an independent variable. During the first three months of the study, participants could set price limits in the UI. In month four, we deliberately disabled the feature, preventing households from setting their preferences for P2P prices. For all P2P trades during that phase, a dynamic (based on supply and demand), yet uniform price was defined for all participants, which ranged between the feed-in tariff and the retail price. The main dependent variable is user preference for one or the other pricing mode; moreover, we examine whether the pricing mechanisms affect user interaction, usability evaluations, and diffusion of DERs. In this context, we examine:

RQ2 To what extent do participants in P2P energy markets value agency (the possibility to self-set prices) vs. the convenience of automation (prices set by the system)?

For the third research objective, we study the benefits of the system perceived by the study participants. To that end, we conducted semi-structured interviews with selected households and conducted an in-depth analysis of the qualitative participant comments. The result is a list of value propositions that can be used to foster the diffusion of P2P energy markets. With this, we aim to answer:

RQ3 What are the perceived benefits of P2P energy markets for individuals?

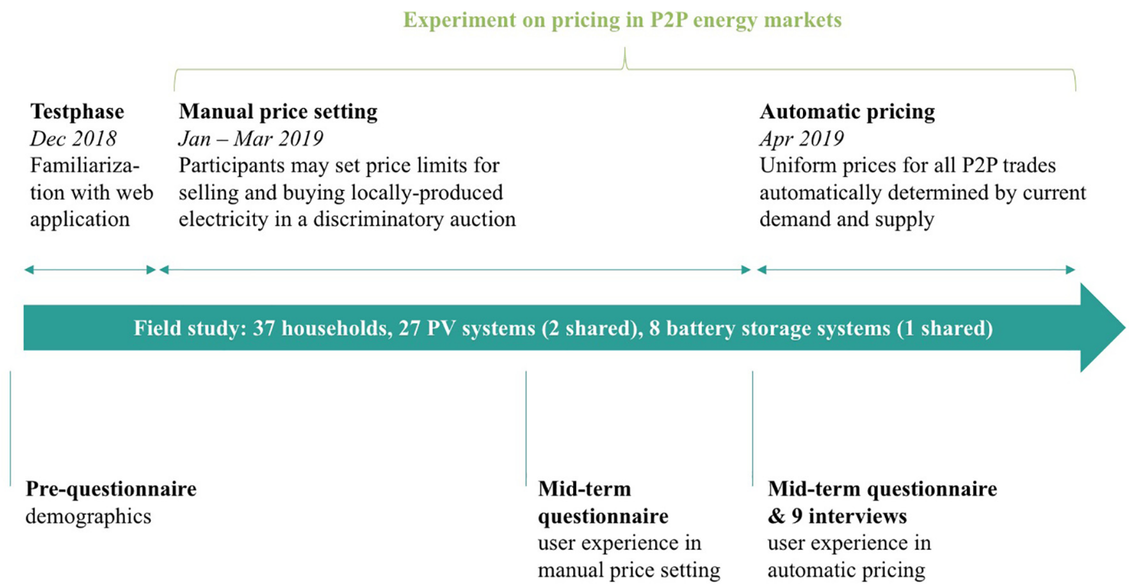

Fig. 1. Experimental design of the study, including the experiment on pricing of P2P energy.

3. Methodology

3.1. Data collection

To answer the research questions above, we conducted a field study with an actual instance of a P2P energy market implemented by a consortium from academia and industry. During the study duration of four months, we determined, in 15-minute intervals each, P2P transactions between all participating subjects that directly impacted the invoice amount of their electricity bills. The necessary smart metering hardware was installed at the participants' houses by the researchers and an electrician from the partnering utility company in the fall of 2018; the web application as the UI with which we examine user interaction and price setting preferences was released to the participants in December 2018. After an initial test phase to familiarize the participants with the technology, the P2P market went live in January 2019. From that moment on, participants could influence their electricity prices in the web application by setting price preferences for the action of locally available electricity. Fig. 1 gives a chronological overview of the study activities.

We applied a mixed methods approach, collecting quantitative and qualitative data. Over the full duration of the study, we tracked households' electricity data using smart meter technology. Participants' interactions with the web application was tracked based on automated log entries in a customized database and with third-party tools, such as Google Analytics (page-wise analytics) and Inspectlet (heat maps). In addition to this measurement data, we collected user attitudes and opinions in surveys and interviews. Survey data was collected at three different points in time: before the field study (demographics and general attitudes), at the end of the manual price-setting phase (i.e., the first three months during which participants were able to set price limits manually), and at the end of the automatic pricing phase with automatic uniform pricing. Participants were invited via email to take the online surveys; those who had not provided an email address received mailed letters with an invitation for the pre-survey (because these people never used the web application, they were not invited for the follow-up surveys). The final data collection is complemented by interviews with a subset of households selected based on diversity criteria (see Discussion section). Overall, we contacted thirteen households, of which nine signed up and participated in an interview. Two researchers independently analyzed these interviews. The sessions were audio-recorded and transcribed. Appendix A presents the demographics of these nine households.

3.2. Sample

To recruit households for the P2P energy market, our partner utility sent out a letter announcing the project to 41 of its electricity customers living in the same area in Walenstadt, SG, a small Swiss town. 37 of these (conversion rate: 90%) opted into the study, of which 25 owned a private photovoltaic system and 7 had a private battery storage installed. In addition, 6 households located in apartment buildings held shares of two PV systems and 4 households shared a battery storage of 30 kW. Only 6 participants were pure consumers without any DERs installed; two of them were commercial entities (a residential home for the elderly and a nursery for plants).

We attribute the high conversion rate to three aspects. First, to the small-town setting, which allows for relatively close interaction between the utility provider and its customers, resulting in a higher level of trust and responsiveness to the locally targeted invitation letters. Second, with a large share of prosumers, the pool of households contacted (as well as the resulting sample) comprises many early adopters of PV systems (and in some cases, batteries), which implies a certain level of interest in and prior exposure to energy-related topics among many participants. Third, the researchers and the utility company invited prospective participants to a local information event in May 2018, and a staff member from the utility company made follow-up calls to non-respondents.

In the following, the terms "participant" or "household" are used interchangeably. Thirty-two households provided us with demographical information in the pre-survey. Twenty-seven of these are owners of the building they live in, and two households live in rented accommodation. Three are single-households, eleven are couples, two are households with three or four adults, and fourteen households are families with children. In most cases, a male member of the household was the one who responded to our surveys; 30 survey respondents are male and two are female. The mean age of survey respondents is 55.2 years (SD = 12.9). Twenty-two households have regular income from employment, while the remaining ten households are pensioners; not a single one of them is unemployed. Many individuals have lived in the region for all of their lives; only six of the households moved to the region since 2010.

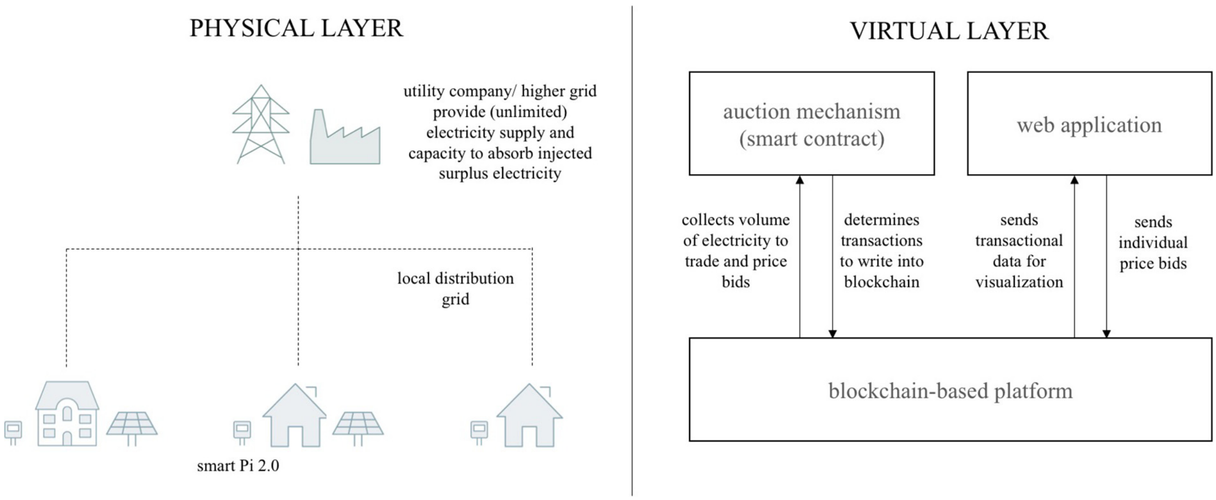

Fig. 2. System components of the peer-to-peer energy market structured on a physical and a virtual layer.

4. System description

The P2P market we built consists of a physical and a virtual layer as outlined in Mengelkamp et al. [18] and in Tushar et al. [51]. In the following sections, we provide a short overview of the developed system with a focus on the components that are relevant for the user interface; a more concise description of the whole system, with its technical components, is given in the related QS-Whitepaper [52]. Fig. 2 visualizes all relevant components.

Key components of the physical layer are SmartPis 2.0, which serve as smart meters installed in all households and measure the energy consumption, PV-generation, and state of charge of the battery storage systems. For the transfer of energy between the participants, the distribution grid owned by the local utility is used for a grid fee. The utility company acts as a backup market participant that either supplies electricity to the community whenever the local DERs do not generate sufficient electricity to cover local demand, or that buys surplus electricity produced by the community whenever local production exceeds local demand. Since energy supply falls under the general supply obligation in Switzerland, the electricity supplied by the grid is, in theory, unlimited. The same applies to the grid capacity to absorb injected surplus electricity. For these transactions, standard retail prices and feed-in tariffs apply according to the utility's terms and conditions.

On the virtual layer, the P2P energy market is implemented as a time-discrete, iterative double auction, with discriminative pricing (for background literature see [53,54]) in which participants can set price limits themselves. The blockchain-based platform (for background literature see [55–57]) collects buy and sell orders for local electricity over a "clearing period" of 15 minutes from each participant. Each order contains both the most recent price preference entered by the participant in the web application and the volume of electricity to be traded measured by the SmartPis (determined ex-post at the end of each clearing period). In case a participant never provided their price preferences as input for the auction, they still participated regularly in the market with default price preferences (same values like the utility provider). Once all orders have been collected, the auction mechanism, a smart contract, is run to clear the market and determine the resulting electricity trades. To that end, the seller with the lowest sales price limit is assigned to the buyer with the highest price limit for purchasing local electricity. The resulting price at which these two households trade electricity is the mean of the two price limits, subject to the deduction of grid fees for use of the infrastructure. Once the market is cleared, P2P energy transactions are written on the blockchain.

A block explorer regularly scrapes the transaction data on the blockchain and provides it to the front end, a web application, in a queryable format. The web application provides details to the users about their energy data and allows them to set price limits. The remainder of this articles focuses on the web application as the user interface (UI) as a means to study user needs, preferences, and interaction with P2P energy markets.

Based on a focus group study with consumers and prosumers (reference blinded for review), we derived the following attributes as UI requirements for P2P energy markets: 1) providing transparency around production and consumption (including associated financial outcomes), 2) enabling users to set P2P price limits, 3) making investments in further DER infrastructure easy, and 4) enabling community relatedness. In line with these requirements, we built a first draft of the application, which we discussed with experts from the energy sector and revised based on their input. Fig. 3 and Fig. 4 present screenshots of the implemented web application and two of its main features: a graphical representation of (a prosumer's) electricity data and the price-setting feature[2]. In addition to these features, the web application offers billing details and an overview of the community and its aggregated electricity data. All graphs in Fig. 3 are interactive on mouse-overs and update according to the user's adjustment of the timeframe. Users can choose timeframes at given intervals (buttons on the left above the load curves), with a calendar feature (on the right), or a zoom band (below). Info buttons on all subpages of the web app give users more details about the elements upon request (mouse-over event), while avoiding cluttering up the web application.

5. Results

The section first provides some general facts about the community to put the results of the research questions into context. During the duration of the study, the community produced 93 MWh of electricity and consumed 162 MWh. Of the self-generated electricity, 33% was directly used by the generating households and 25% was exchanged within the community; thus, the community self-consumed 58% of the electricity it produced. The remaining 42% was injected into the grid. Conversely, the community was self-sufficient by 33% (19% self-sufficiency of single households and 14% achieved by locally exchanging electricity). 67% of the electricity consumed was provided by the grid (see Appendix B for a visualization).

[2] All other features can be found in Appendix D.

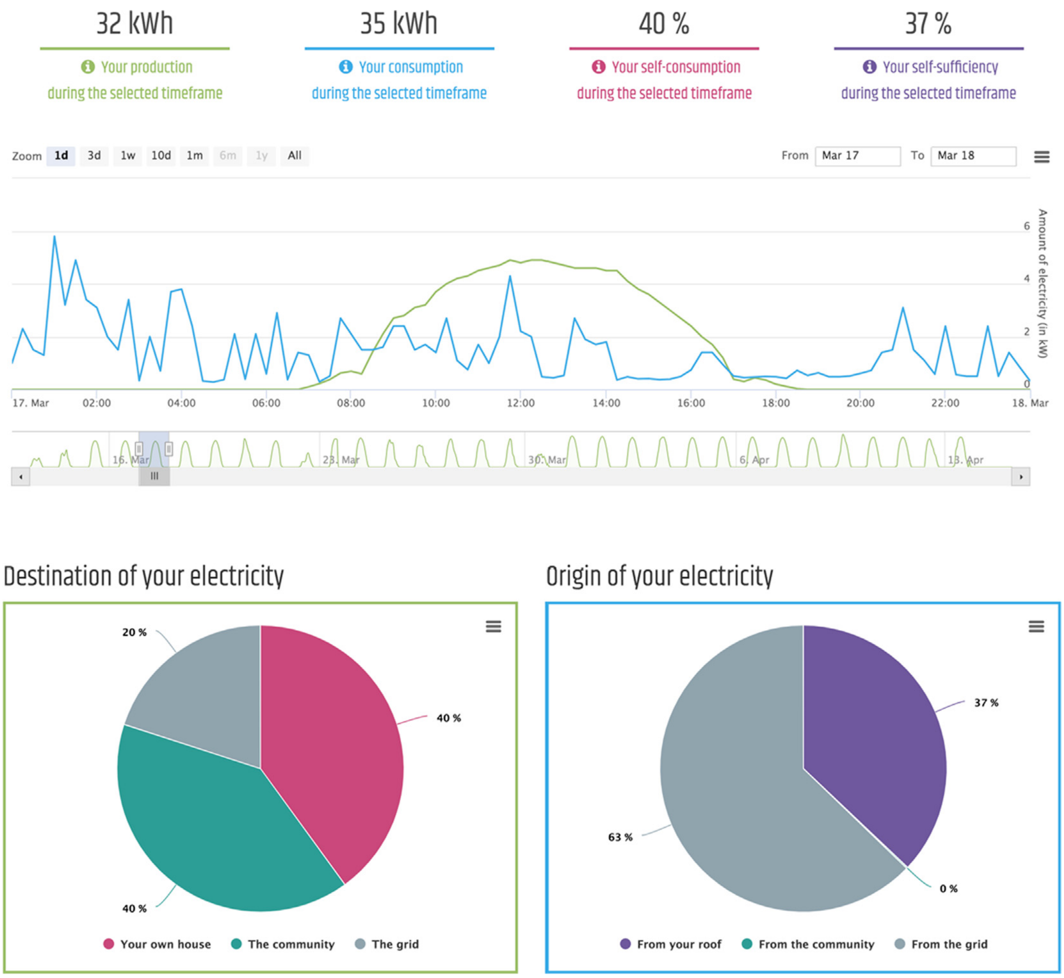

Fig. 3. Personal electricity data. Participants get an overview of their production and consumption with summary values on top, load curve in the center, and pie charts visualizing destination and origin of electricity at the bottom.

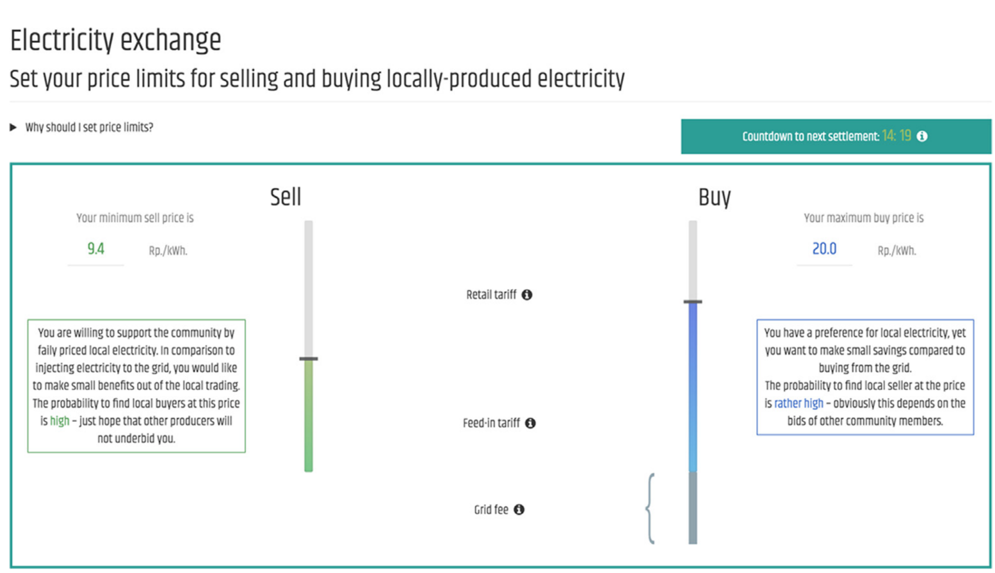

Fig. 4. The price-setting feature. Participants can set price limits for selling and buying electricity on the local market. Feed-in and retail tariffs are given as reference points and are used as default values.

5.1. Interaction with the UI of the P2P energy market

The following section addresses RQ1 and describes how individuals interact with the UI of the self-built P2P energy market. In line with the sensemaking framework (see section 2.3), the results are categorized into noticing, interpreting, and taking action.

5.1.1. Noticing

The first stage of the sensemaking approach considers whether individuals absorb the provided information. To that end, we report results related to the two implemented forms of interaction: frequency of access to the web application (pull-basis) and open rates of monthly email reports (push-basis).

28 of 37 field study participants created an account and can therefore be considered (at least as one-time) users. The remaining nine households are classified as non-users. Among the non-users, five had answered the first survey; none of them completed the second or the third survey[3]. Similar to a usage visualization used in Khosrowpour et al. [58], Fig. 5 shows a daily usage plot of the web application for the 28 users. A green rectangle indicates that the household has used the application at least once on the given day (prosumers in light green, consumers in dark green). The tracking logged a total of 1,303 unique sessions, and there was not a single day without any logins since the launch of the web app in mid-December. While monthly logins decreased slightly over time, the number of monthly active users of the web app is remarkably high and quite stable: during the field phase, the number of monthly active users ranged between 18 and 25, with an average of 22.4 active users per month. In other words, between 64% and 89% of the participants who created an account logged in at least once every month (79% on average).

A Mann-Whitney test for differences in non-parametric data between two independent samples did not reveal a significant difference in frequency of usage sessions of prosumers (median = 15.0, light green) and consumers (median = 17.0, dark green), $U = -0.52$, $p = .60$. A subset of eight participants used the application a couple of times per week, or even almost on a daily basis (H1–H8). The group in the middle of Fig. 2 used the application on a less frequent basis, with more or less regular usage patterns, depending on the household (H9–H18). The least active group used the app on a very irregular basis. Nevertheless, most of them logged in at least once in month four after the launch (H19–H27), while H28 only logged in once and never returned to the application. The interview data was collected from participants in all three different usage groups.

In addition to access to the web app, participants received monthly reports via email on the first day of each month. Remarkably, there is no increase in the activity on the web app after the report was delivered (see beginning of each month in Fig. 5). The email provider used for sending out the reports allows us to track how often people opened the emails with a customized image in each email. The opening rates for the monthly reports are as follows: 88% in January, 72% in February, 82% in March, and 77% in April. Interviewed households generally showed high appreciation for the reports as they provide a concise overview (H8, H26) and remind them about the ongoing project (H9, H22).

5.1.2. Interpreting

The second stage of the sensemaking approach evaluates how individuals interpret the provided information. In the following, we present purposes for using the web application and consider how individuals make use of the UI elements to learn about their energy-related behavior.

Fig. 6 lists the different usage purposes that participants stated. To that end, a survey asked participants to distribute a total of 100 points across the following categories: receiving market data, receiving personal electricity data, receiving community electricity data, receiving financial transparency, setting price limits, or other reasons. Insights into market activity and users' own electricity data seem to be the main drivers for using the web app (Fig. 6).

To get a better understanding of how users engage with the different UI elements, we asked interviewees to identify the elements they paid most attention to. Interviewees consistently listed the elements related to their personal electricity data (Fig. 3) and a quick overview on the landing page with current production, self-sufficiency, local trades, and P2P price. Other elements that present, for instance, community data or an overview of the participant's financial aspects of the P2P market, were far less popular. These findings are supported both by usage purposes collected with participant questionnaires (Fig. 6) and by the Google Analytics statistics that tracked user behavior in the web application (Table 1[4,5]). In contrast to the self-reported data on usage purposes (surveys) and favorite elements (interviews), the activity logs show that the subpage featuring the price-setting functionality interestingly received a relatively large amount of attention from users ($N_{pagevisits} = 1140$). While the feature was not initially perceived by us as very important, it was in fact utilized a lot: our database recorded 343 price changes between January and March (the median number of price changes per user is 6). The usage data further indicates that many users made efforts to analyze their load profiles. As Fig. 7 shows, and as indicated in a couple of interviews, individuals made usage of the different timeframe selection possibilities, zoomed into their data, and tried to connect spikes to certain appliances. These efforts regarding disaggregation of load curves may foster load-shifting, which we will describe in detail in the following section.

5.1.3. Taking action

The third stage of the sensemaking approach relates to taking action based on the learnings generated from using the system. The following analysis is structured in two parts: 1) word-of-mouth measured by the degree to which participants spread the word about the P2P energy market within their social circles, and 2) behavior change regarding energy consumption measured by (self-reported) load-shifting activities.

Regarding word-of-mouth about P2P energy markets, participants indicated on a scale ranging from 1 = no/not yet to 4 = frequently whether they had talked about the project with other study participants in their neighborhood or with friends and family not participating in the project. The results indicate that project participants discussed the project rather rarely with other participants (M = 2.11). To many interviewees it was not clear which neighbors participated in the project and which neighbors did not. To address this, two households asked for more community building events to get to know their electricity producers or buyers (H14, H26). Yet, several participants did discuss the project with friends or acquaintances not involved in the project (M = 2.68). The study participants estimated that the majority of individuals with whom they discussed the project (73%) expressed a high level of interest in joining such a market. Obviously, these numbers need to be interpreted with caution, as it is plausible that the participants were more likely to bring up the topic to individuals who they deemed interested in the overall topic in the first place. All interviewees

[3] In fact, four of these households did not even provide us with an email address, which either indicates a low interest in the study or a low affinity for technology.

[4] Table 1 indicates a negative correlation of subpage visits and study duration. Considering the fact that sessions remained stable after a usage high in the first two months (Fig. 5), we conclude that households learned how to use the web app and achieved their goals (e.g., price setting, insights into data) with fewer page visits than at the beginning of the study when they were exploring the functionalities provided.

[5] Screenshots of all subpages are attached in Appendix D (only available in German)

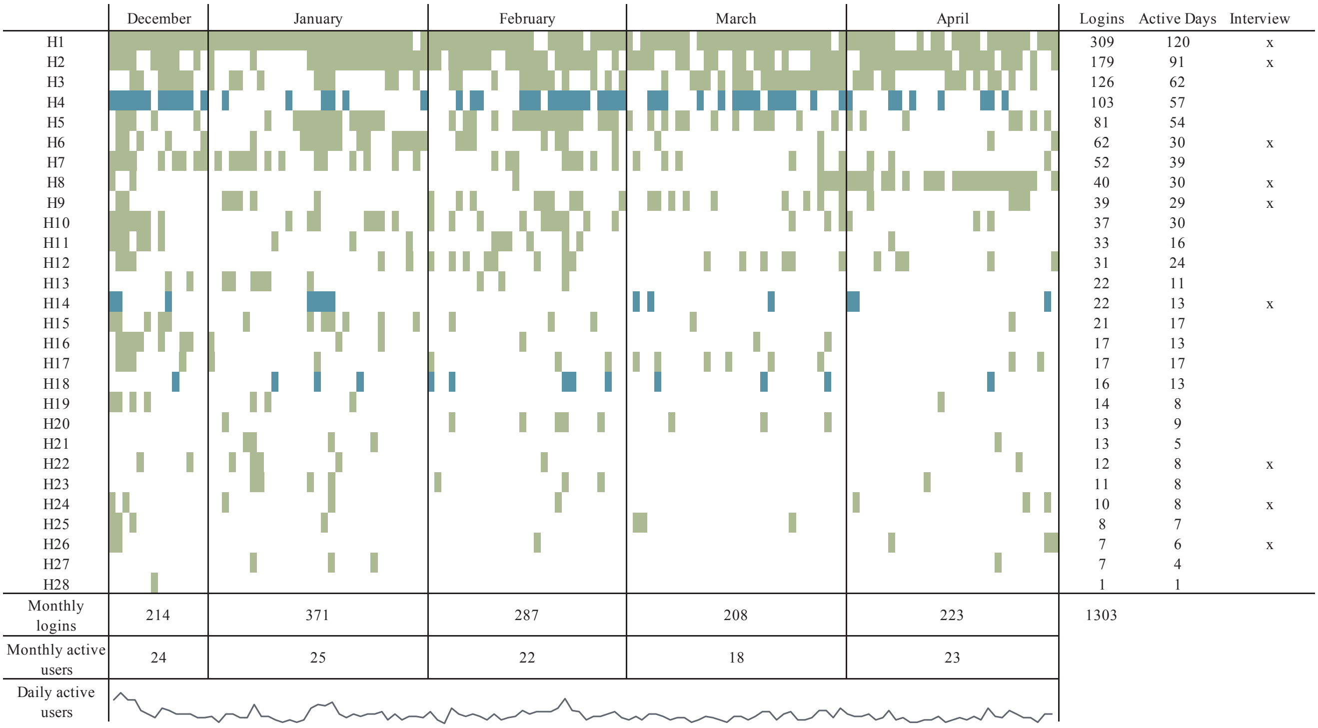

Fig. 5. Web application usage plot. Filled green rectangles indicate at least one login by the household on that day (light green for prosumers and dark green for consumers). Most participants used the application rather frequently.

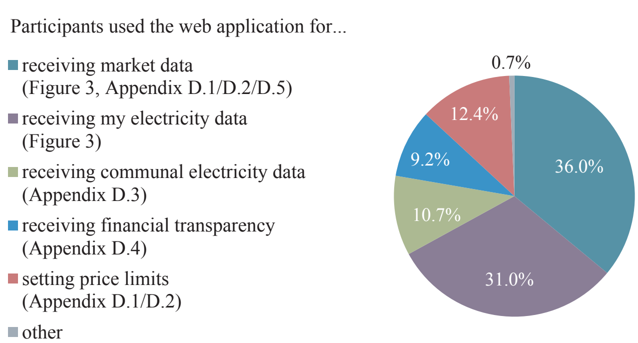

Fig. 6. Usage purposes during the manual price-setting phase. Participants valued the web application primarily for getting insights into market activity and their own electricity data.

regarding future DER diffusion both on a micro level (H8, H14), and in realizing the energy transition on a macro level (H1, H8, H9, H14, H22, H24, H26).

Regarding behavior change in participants' energy consumption, the temporal match of energy generation and demand (see green and blue line graphs in Fig. 3) plays an important role. For prosumers – and, in P2P energy communities, also for consuming households – it makes sense to consume energy while it is being produced, i.e., during sunshine hours. This is not only of financial interest, but it also avoids the necessity of storing or transporting the electricity. In Switzerland, households traditionally have economic incentives to consume energy during the night (day/night tariffs). The introduction of DERs now imposes a paradigm shift and requires households to rethink and restructure their routines if they want to maximize the potential of their DERs. Most interviewed households brought up the topic of load-

Table 1
Usage statistics per subpage extracted from Google Analytics.

	Page visits					Average time spent on page (in min)					Total visits	Avg. time
Subpage	Dec	Jan	Feb	Mar	Apr	Dec	Jan	Feb	Mar	Apr		
Landing page (Appendix D.1)	403	716	463	527	368	01:20	00:45	00:41	01:12	01:51	2,477	01:09
Personal electricity data (Fig. 3)	213	450	349	250	209	01:24	01:37	01:24	01:34	02:04	1,471	01:36
Price setting (Appendix D.2)	218	351	324	180	67	01:52	01:28	01:50	01:22	01:21	1,140	01:34
Financials Appendix D.4)	99	208	185	170	114	00:47	00:43	00:55	00:40	01:41	776	00:57
Community electricity data Appendix (D.3)	91	165	119	66	46	01:09	02:16	01:26	02:03	02:53	487	01:57

strongly supported the idea of extending the community beyond its initial boundaries to a communal, regional, or national level. Several households stressed the importance of the P2P energy concept shifting without being asked about it. In that context, six prosumer households in our sample reported that they have started shifting their energy consumption to sunshine hours after having installed their

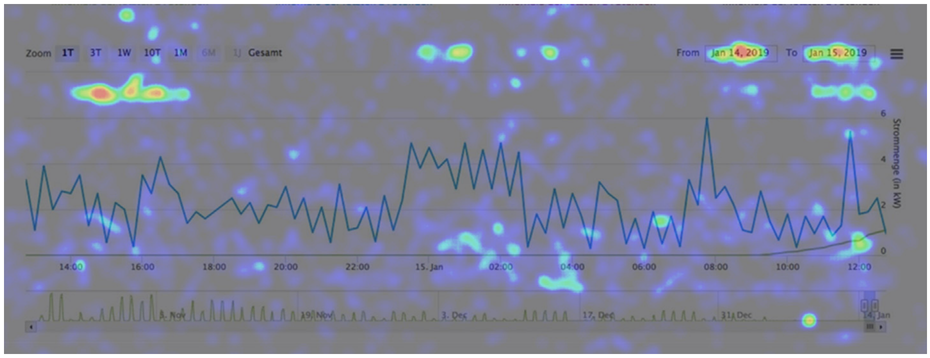

Fig. 7. Heat map of the subpage for personal electricity data (based on mouse movements of all participants). The participants used different timeframes to interpret their load curves.

DERs. Two further households explicitly stated that they began to engage in load-shifting activities due to the project.

5.2. Pricing mechanisms in P2P energy markets

To answer RQ2, we evaluated user preferences and the impact of two different pricing mechanisms on interaction-related outcomes (interaction with portal, usability evaluations) as well as on diffusion-related outcomes of P2P energy markets (DER investment intentions, word-of-mouth in the neighborhood). As described above, participants could actively participate in the P2P energy pricing in the first three months of the study, and together made a total of 343 price changes during that period. This means that 35.8% of usage sessions tracked in January involved a price change, and 30.1% of February sessions and 20.8% of March sessions, respectively. In month four, we disabled the price-setting feature and defined a uniform price for all participants (yet one that was still dynamic, depending on local demand and supply). We used the following data for our analysis: 1) activity logs (refer to Fig. 5), 2) qualitative interview data from nine households, 3) survey data on the price-setting phase (N = 19), and 4) survey data on the automatic pricing phase, including the user preference (N = 24). From a total of 17 households, all quantitative data (surveys and activity logs) is available.

Based on user preferences and their interactions with the web app, we identified different user segments: 11 out of the 28 users (i.e., households that had created an account) wanted to participate actively in the pricing of P2P energy and set their own price limits. The interview data suggests that this group values the gamification character, the idea of a free market, and the fact that they don't have to trust a third party in determining prices for their surplus (respective of locally purchased) electricity. By contrast, 13 households preferred automated pricing, i.e., uniform market prices defined by the system (based on current demand and supply in the community)[6]. They seem to value automated prices for reasons of convenience and simplicity. Remarkably, the correlation of user preference and usage frequency is rather counterintuitive: those who used the portal more often tend to prefer automated prices. Regression analysis with "pricing mechanisms preference" as the dependent variable shows that usage explains 16% of variance in the preference for the pricing mechanism (marginally significant effect of b = 49.85 at p = .057). User type (consumer/prosumer) or the frequency of previous price changes do not affect the preference for one or the other pricing mechanism. As a result, we segment our study participants into the following categories: individuals who used the portal for data exploration and who prefer to set their own prices (30%), individuals who used the portal for read-only purposes and who prefer to rely to externally defined prices (35%), and non-users (24%) or non-respondents to the survey questions (11%). Fig. 8 visualizes the different user clusters.

The usage data further suggests that the different pricing mechanisms did not affect participants' usage of the web application. The general acceptance of the P2P energy market, however, decreased significantly after the period with automated pricing began, as indicated by a paired sample *t*-test. At the end of the three-month period with manual price setting, the general acceptance of the market was 4.71 (SD = 0.59), measured on a 5-point Likert scale, translated as *good acceptance* to *very good acceptance* on average. By contrast, the acceptance indicator dropped to 3.53 (SD = 1.01) translated as *undecided* to *good,* t(16) = 4.78, p = .0002, after the automated pricing phase. However, this result might also be an artifact of the within-subject study design (a study design with crossed treatments was not feasible for technical reasons and due to the small sample size). In other words, we cannot rule out that the decrease in the general acceptance rating could be due to general time trends (e.g., fatigue of participants). With regard to usability evaluations, participants' rating after the automated pricing phase was 5.35 on a 7-point Likert scale; thus, it was similar and not significantly different from the usability rating in the manual price-setting mode, where it had received a score of 5.41. Likewise, during the automated pricing phase, the participants indicated very similar reasons to those given in the manual price-setting phase (see previous sections) for having used the web application in the month in which the price-setting functionality had been disabled. The two main reasons for using the web application were to receive insights into market data (40.0%) and personal electricity data (25.3%). Among these usage purposes, no significant differences between the pricing mechanisms can be found. Table 2 presents the statistical test results for all variables discussed in this paragraph.

Likewise no significant differences for DER investment intentions or word-of-mouth can be found (Appendix C). Again, this result might be due to the fact that study participants considered the timeframe (roughly four months) to be too short to make up their minds. As a result, the price-setting function has not affected the way users interact with the web app and how they perceive this interaction. Yet, disabling the function has decreased the general acceptance of a P2P energy market for those people who support the manual price setting.

5.3. Perceived benefits of P2P energy markets

The third research question aims at gathering the advantages of P2P energy markets perceived by the study participants. Based on these, value propositions of P2P energy markets could be derived and could be compared to P2P energy market benefits identified in literature. We structure our findings of the in-depth analysis of the semi-structured interviews with nine households according to Reuter and Loock [28], who found that individuals would be willing to join P2P energy markets for the following reasons: environmental, economic, technological/

[6] Four of the users did not respond to the survey, resulting in missing data points for their preferences.

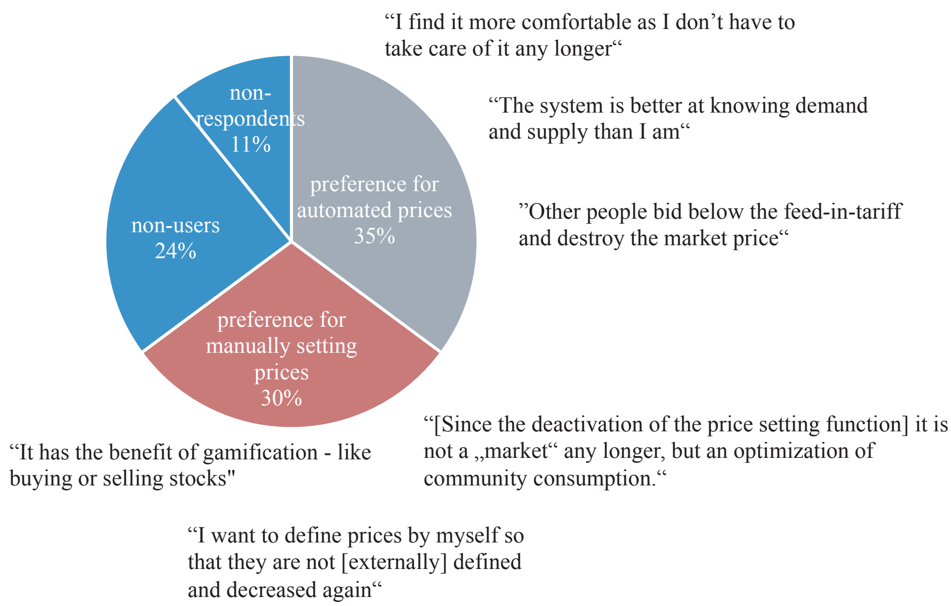

Fig. 8. Segmentation of users by activity level (price-setting preference and system usage) in the P2P energy market.

Table 2
Statistical tests for usage-related dependent variables.

DV	M_{MP}	SD_{MP}	M_{AP}	SD_{AP}	t	dof	p
Acceptance of the P2P market with its price feature	4.71	0.59	3.53	1.01	4.78	16	0.0002
Usability	5.41	0.92	5.35	0.83	0.22	16	0.83
Usage purposes: market data	35.6	16.9	40.0	32.3	−0.52	16	0.61
Usage purposes: own electricity data	30.9	12.4	25.3	25.3	0.90	16	0.38

infrastructural, political/independence, and social/community motivation.

Environmental – All but one household mentioned the environmental friendliness of PV electricity and appreciated that the concept of P2P energy markets is based on environmental friendliness. In that regard, the project seemed to encourage them to engage more in load-shifting activities (as above mentioned). Two households (H8, H14) further stated that the project is a step toward the 2,000-Watt Society, an energy-political concept to limit energy demand and to support renewable energies that is well-known in Switzerland (national and regional referenda involved the concept and many media articles covered the concept). Additionally, three households referred to raising awareness of energy topics: one household reported they are now pay more attention to the topic (H22) and two more households mentioned it was important to raise awareness among the general population about the source (form of generation) of electricity (H14, H26).

Economic – Most households reported having economic incentives for participating in the P2P energy market, or, to be more precise, they hoped to be able to sell their electricity at a higher price than they were being paid to inject electricity into the grid. In that regard, many of them attached great importance to P2P energy markets in the light of decreasing feed-in tariffs. Three households further referred to lower grid fees when exchanging electricity locally (which were implemented for the project). As a result, individuals in the sample perceived that P2P energy markets could reduce the uncertainty of DER investment profitability [8,18], and three households even stated that projects like these could be an incentive to invest in further renewable energies (H8, H9, H14). Nevertheless, three of the households who had indicated financial motives for their participation in the project mentioned that it was not entirely about the money, but more about the general movement toward doing good (H1, H6, H9).

Technological/infrastructure – The majority of households presented arguments that relate to technological exploration or infrastructure. Six households (H1, H2, H6, H8, H14, H22) particularly valued the possibility of reading their load curves (electricity demand) and manually associating spikes to certain appliances with the web app. The remaining three households said they had previously been doing this with other apps from their PV manufacturer. Likewise, two households stated that they compared their data with each other (H1, H9). In the general context of data exploration, some participants mentioned that they liked the project for its innovativeness (H14, H22), for their personal interest in technology in general (H14), or for its gamification character (H1, H14).

Political/independence – Three households explicitly mentioned that they liked the free market character of the project, which allowed them to define prices (H8, H14) or to express ecological preferences regarding their electricity supply (indicated by their willingness to buy/sell) (H26). All but one household stressed the importance of locally optimizing demand and supply, and stated that they would be interested in seeing where their electricity comes from or where it goes. Five households highlighted in particular that the region would depend less on other regions for their electricity supply, and fewer transmission lines would then be needed at the national/macro level (H2, H6, H8, H14, H22). Two households further mentioned that projects like these would reduce the need to import electricity from other countries (H2, H9). In that regard, one interviewee compared a local energy market to the trend for regional food in supermarkets and stressed that people should care about the origin of their electricity just like they care about where their food comes from (H26).

Social/community – Four households (H1, H9, H14, H24) felt the project was contributing to the social community – at least to a minimum degree. Interestingly, the only interviewed consumer household spoke about *our community* while none of the prosuming households used this term. For instance, H1 and H9 frequently discussed the project and price strategies with each other. H14 and H26 stated that the feeling of community could be further extended by a discussion forum in the web app or by organizing physical community get-togethers. H1 and H9 stated that they would be willing to actively recruit their neighbors for the project, because they thought many more neighbors would be interested in joining (refer to survey data in previous section) and also because it would result in more buyers in the

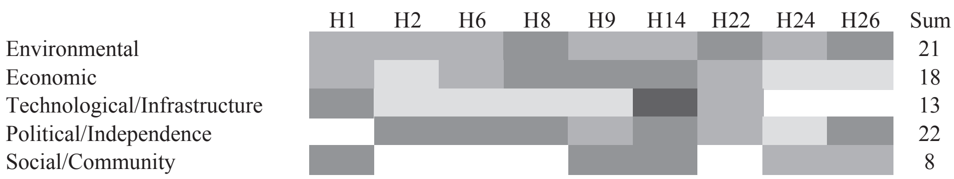

Fig. 9. Benefit analysis conducted on interviews. The greater the number of topics a household brought up, the darker the cells.

community (which often faced surplus generation because of its relatively high production capacity).

Fig. 9 is a graphical representation of the described perceived advantages. If a household brought up a certain topic, we coded it as a 1 in the background. The darker a cell of the main category, the more topics were raised by the household during the interview. Cell colors represent the sum of different subcategories mentioned (e.g., ecological aspects of PV, contribution to 2,000-Watt Society, incentive for DER investment) within the five main categories (e.g., environmental) on a percental level: white = none of the topics within main category were raised; light grey = 1–24% of topics were raised; medium grey = 25–49%; dark grey = 50–74%; anthracite = 75–99%; black = all topics were raised. The sum column indicates how often subcategories were brought up in total. The graphical representation shows that households perceived strongest advantages on the environmental, economic and political/independence dimensions – or, in short, households perceived P2P energy markets as green, local, and fair.

Perceived disadvantages or risks – The interviewed households generally had a very positive opinion of the project and wanted it to be extended. However, one household worried about their relationship with the utility company and possibility of resulting changes in service from the utility in case the household were to buy less electricity from the utility in the future. Another household expressed concerns regarding the general user acceptance of P2P energy markets, as many individuals may not be sufficiently informed and aware of the context for projects like these.

6. Discussion and limitations

This study is one of the first studies to examine user behavior in P2P energy markets, whose concept builds on households that contribute to the local market by either selling their surplus electricity or creating a demand for electricity. To that end, we developed a P2P energy market including a web application as a user interface for the study participants. The article investigates how individuals interacted with the P2P energy market, whether they wanted to be included in the pricing of P2P energy, and which benefits they perceived. The main findings of the explorative field study with a focus on the user perspective are threefold and lead to the following implications:

First, usage statistics show that study participants frequently interacted with the web app, which is in contrast to many other studies that have assessed user engagement with products and services in the energy sector. Specifically, the UI was used on average 9.7 times per day in total by the 28 households who participated in the P2P energy market and had registered for the app. Moreover, the monthly active users remained stable over the full course of the 4.5-month study (roughly 20 monthly active users as Fig. 5 indicates). Users reported utilitarian aspects (e.g., data transparency) and hedonic aspects (e.g., convenient usage). Activity log data, answers to surveys, and interviews indicate that having access to their own electricity data and knowing about the electricity's origin and destination were the main drivers for participants to use the UI. As a result, the study empirically validates our previous findings on user needs in P2P energy markets (described in a working paper currently under review). We conclude that individuals in our sample were interested in the market activity of a P2P energy market, which is a first signpost that the concept could find approval from the general population.

Second, we considered the transactions between participants and tested different price-setting mechanisms. Based on their real-world engagement with a P2P energy market and their stated preferences in surveys and interviews, the 37 households can be categorized into the following user groups: those that want to actively set prices (30%), those that prefer automated prices by an information system (35%), and non-users or non-respondents to the survey (35%). In that regard, future P2P energy markets should introduce a combination of smart agents that can place price bids on behalf of the participants based on their indicated preferences, as well as providing an option for participants to set prices themselves. Developers of such smart agents for P2P energy trading can find inspiration from existing solutions in the sharing economy. For example, Wheelhouse is a plugin for Airbnb hosts that determines accommodation pricing schemes based on different strategies that the host can choose from (e.g., maximum occupancy, highest rate per night, self-set rates) [59]. We therefore conclude that future technology can address different user preferences regarding active involvement in P2P energy pricing by allowing for both automation and agency.

Third, an impact analysis based on interviews with nine households (selected based on diversity aspects) suggests that P2P energy markets might increase the perceived presence (=saliency) of renewable energies, and that the concept could promote load-shifting activities. As the sample size of the presented field study does not allow for quantifying the effect of load-shifting based on actual energy data, future larger-scale field research is needed to derive more generalizable conclusions about the actual sustainability impact of P2P energy markets. The survey and interview data further suggests that the majority of participants support the general concept of P2P energy markets, and that many of them have already recommended the concept via word-of-mouth to their neighbors, friends, and family. While two households installed a battery storage system in response to the announcement of the study, future research needs to empirically quantify the realistic impact of P2P energy markets on renewable energy adoption among the broader population. As a result, future research should investigate whether P2P energy markets are a vehicle for sustainable energy transforming the identified value propositions *green*, *local*, and *fair* into observable and measurable real-world benefits of P2P energy trading.

Despite our best efforts, the insights generated in this explorative field study are subject to contextual, situational, and methodological limitations, which raises the question to what extent the findings can be generalized to the broader population. Several limitations relate to the relatively small sample size, which is mainly due to technical and financial reasons. In fact, one of the main reasons why there are hardly any existing P2P market implementations in the field is the lack of suitable technical infrastructure, i.e., certified off-the shelf smart meters with the communication capabilities required for a P2P market. Consequently, we have developed ourselves a technical solution that fulfilled the communication requirements of the pilot field test, using SmartPis (i.e., smart meters that host a single board computer and a power electronics unit; more detailed information on the technical infrastructure is available in [60]. This technical solution, however, was associated with substantial development costs and maintenance efforts. To keep costs, maintenance efforts, and risks of the project at a reasonable level and given budget constraints, we had to limit the number of participating households to less than 40.

Given our opt-in recruitment strategy, the results may be subject to volunteer selection bias, which might distort the external validity of the findings [61]. Moreover, our sample of participants comprises many early adopters of PV systems, who are likely to be more interested in sustainability topics in general and to have at least a minimal technical understanding of the topic of energy supply and demand. Today's prosumers are typically middle-aged individuals who own a house and are rather well-off in terms of education and income [62]. Yet, as costs for PV systems are falling drastically [4] and public awareness of climate change is rising [63–65], the share of prosumers in the population is expected to increase considerably in the next decades. Nevertheless, in an ideal setting, we would have recruited more consumer households to join the study (also to enhance competition on the consumer side). Yet, this was not possible for administrative and financial reasons (installing the smart meters was a costly and time-intensive process). On the other hand, we did not find significant differences in web application usage between prosumers and consumers, which relativizes the prosumer bias to some extent. To further mitigate these potential issues, in the selection of households for the interviews, we went to a great effort to cover a broad and diverse spectrum among the study participants, including prosumers and consumers, high-, low-, and non-users of the web application, older and younger participants, men and women, etc.

The small sample size obviously imposes some restrictions regarding the experimental design of the study. In particular, we would ideally have included a control group that would have had access to a similar user interface with real-time data, but without the option to trade within the community. That way, we would be able to better disentangle the effect of P2P energy trading from the mere effect of having access to real-time data that the web application offers. However, due to the technical and financial limitations regarding the sample size, including a control group would have come at the price of a substantial reduction of the already small number of participants in the local energy market. Given the novelty of the self-built technology and anticipated technical issues, in addition to typical attrition rates in field studies, we might easily have ended up with less than a dozen participants in each group completing the study with valid data. Further taking into account the large variance in the load profiles, comparisons between a few participants in each group would not have yielded very meaningful results.

Likewise, from a methodological point of view, we would have preferred to cross the treatments for the experiment on the pricing mechanisms (i.e., one group starts with the price-setting functionality and one without, and they switch at mid-term). Unfortunately, this was not possible due to technical reasons and implementation efforts. Another shortcoming of the study is the high involvement of the partnering utility, media, and researchers in the project. We hosted two information events, one for recruiting households and then a kick-off event at the launch of the project. The local utility, which was responsible for the recruitment of study participants, put great effort in identifying leads and converting them to participants. Finally, as Switzerland's first P2P energy market, and given the current wave of interest in sustainability/climate change topics as well as blockchain technology, the project received substantial positive media coverage, which may also have influenced participants' interest in the topic and their evaluation of the project. Even though we tried to keep communication with the participants to a minimum, the researchers themselves were involved in field visits to install the smart meters or to help the households in cases of technical problems or comprehension issues. Nevertheless, as one of the first real-world P2P energy markets worldwide that focuses on user aspects, the project provides empirical insights into user behavior in P2P energy markets and thus valuable findings to complement existing research, which had relied primarily on responses to hypothetical scenarios.

7. Conclusion

This article contributes to the rapidly evolving discussion of P2P markets with first evidence on user behavior collected in a real-world instantiation of a P2P energy market. In particular, the price limits that participants set in our study for trading solar energy in the community were not hypothetical price indications, but actually impacted the participants' electricity bills. The article addresses various research calls from the P2P energy research community targeting socio-economic factors [8,18] and P2P energy pricing [7,28]. The article provides first evidence that involvement by households in P2P energy markets can contribute to the energy transition for the following two reasons. First, P2P energy markets may foster sustainable practices, like self-consumption or load-shifting, by increasing the salience of these topics and by facilitating access to relevant data to act upon. Second, local aspects of electricity (share of electricity being sold to/bought from the community) seemed to drive user engagement and might therefore foster the future diffusion of DERs. While this is one of the first articles to study user behavior in a P2P energy market in an empirical setting in the real world, future research should evaluate the generalizability of the findings in larger experiments and in different socio-economic contexts.

CRediT authorship contribution statement

Liliane Ableitner: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Verena Tiefenbeck:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Arne Meeuw:** Software, Data curation, Conceptualization. **Anselma Wörner:** Software, Methodology, Data curation, Conceptualization. **Elgar Fleisch:** Conceptualization, Supervision, Funding acquisition. **Felix Wortmann:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

At the time of submission there are no financial or personal interest conflicts of the authors.

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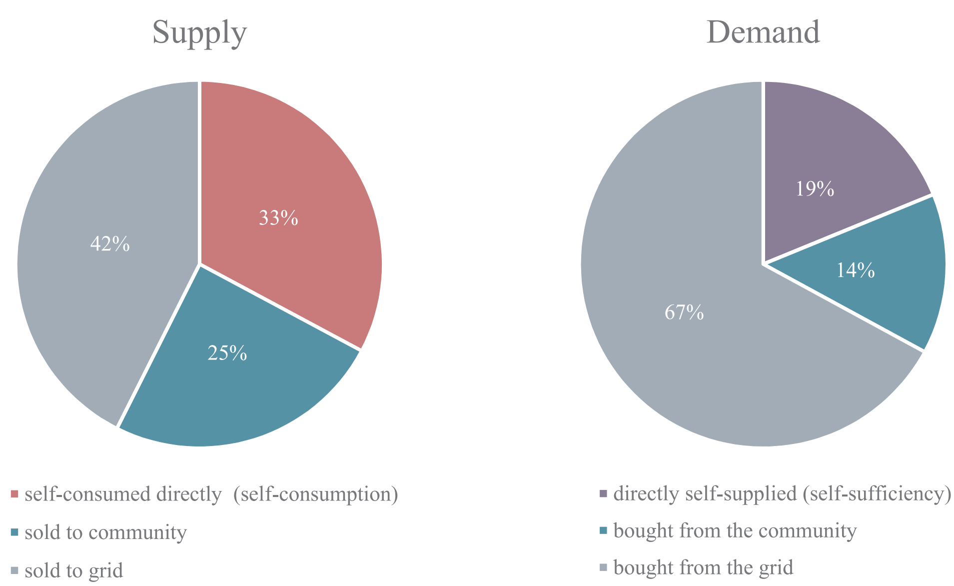
Appendix A. Demographics of interview participants

ID	Demographics
H1	family with teenagers
H2	retired couple
H6	family with young children
H8	retired couple
H9	retired single
H14	family with teenagers
H22	family with young children
H24	retired couple
H26	family with young children

Appendix B. Electricity produced (left) and consumed (right) by the community

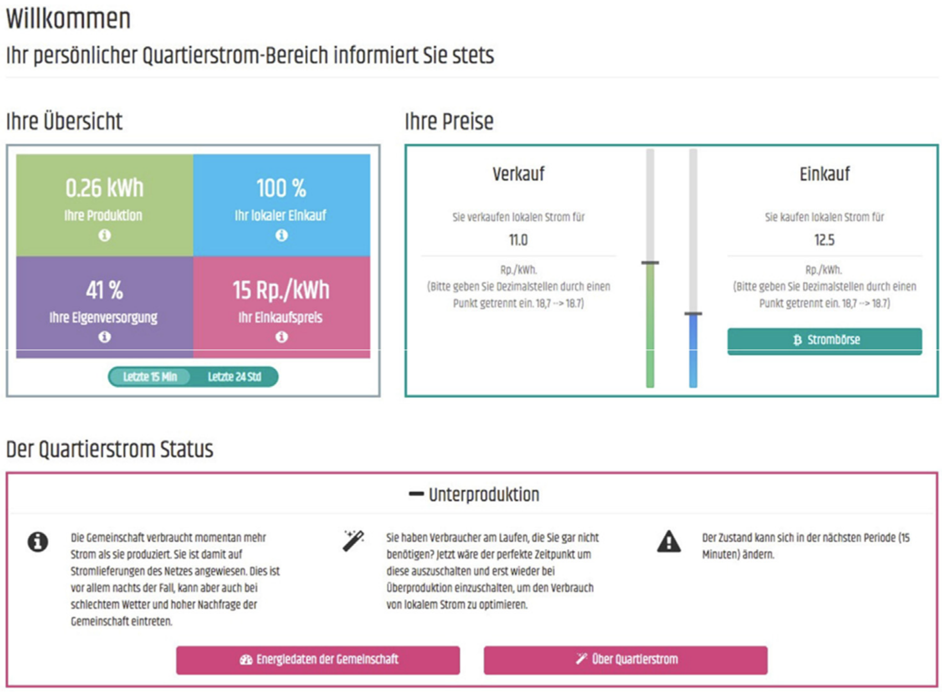


Appendix C. Statistical tests for diffusion-related dependent variables

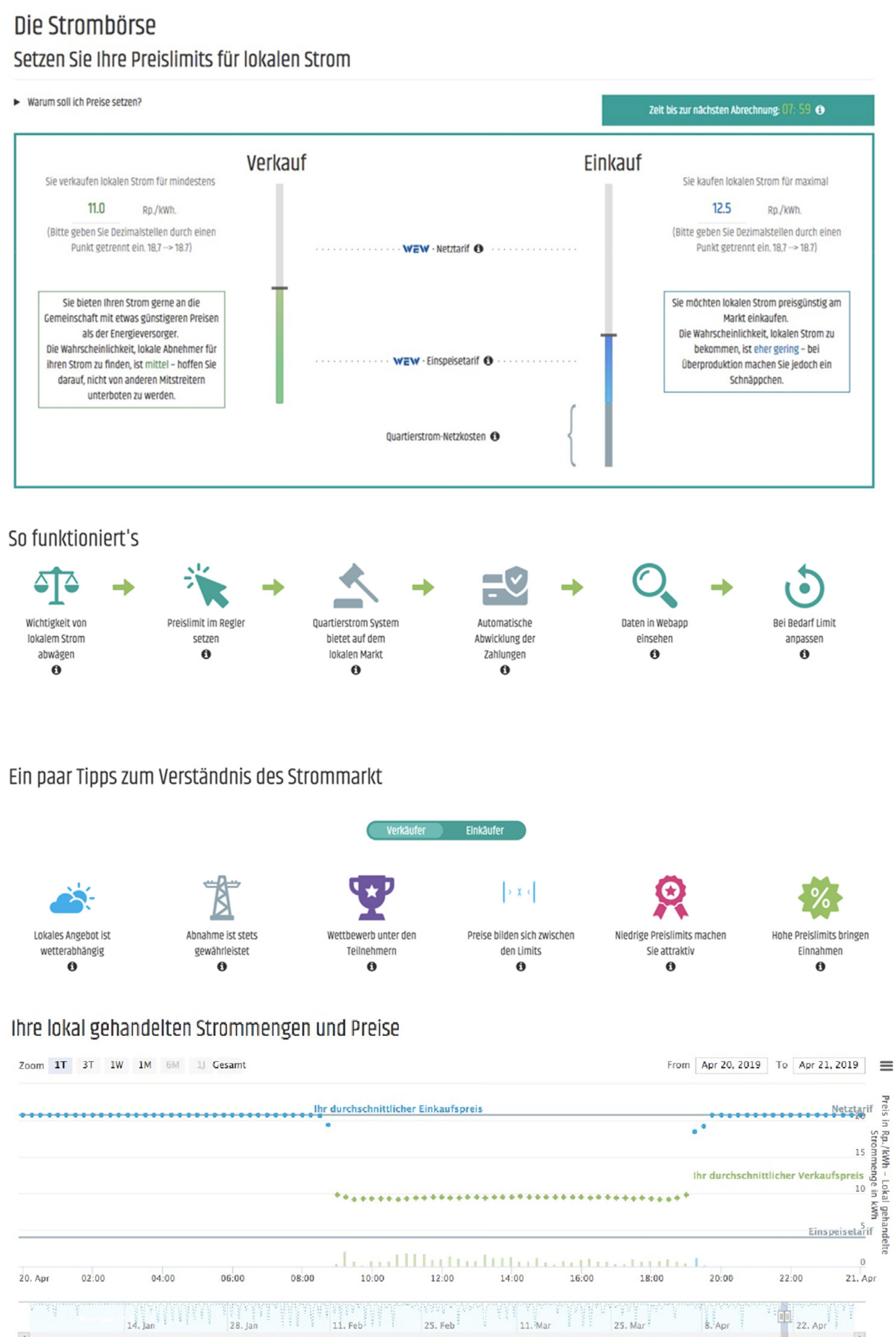
DV	M_{MP}	SD_{MP}	M_{AP}	SD_{AP}	t	dof	p
Investment intentions: (further) photovoltaic system	1.75	1.18	2.25	1.24	−1.52	15	0.15
Investment intentions: (further) battery storage	3.19	1.38	2.94	1.12	0.72	15	0.48
Investment intentions: shared infrastructure	1.93	1.00	1.81	0.83	0.40	15	0.70
Word-of-mouth: Conversations with other participants	2.18	0.73	2.18	0.95	0	16	1.0
Word-of-mouth: Conversations with externals (non-participants)	2.76	1.03	2.53	1.03	1.07	16	0.30

Appendix D. Screenshots of the web app (in German)

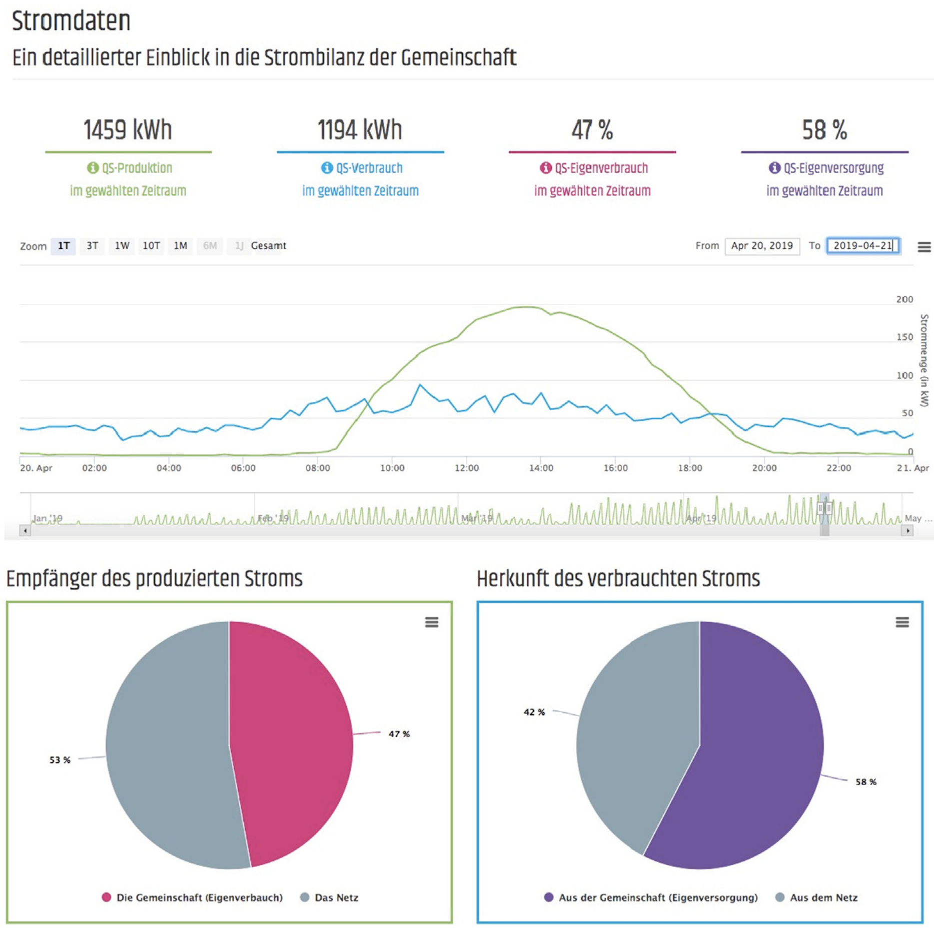
(1) Landing Page



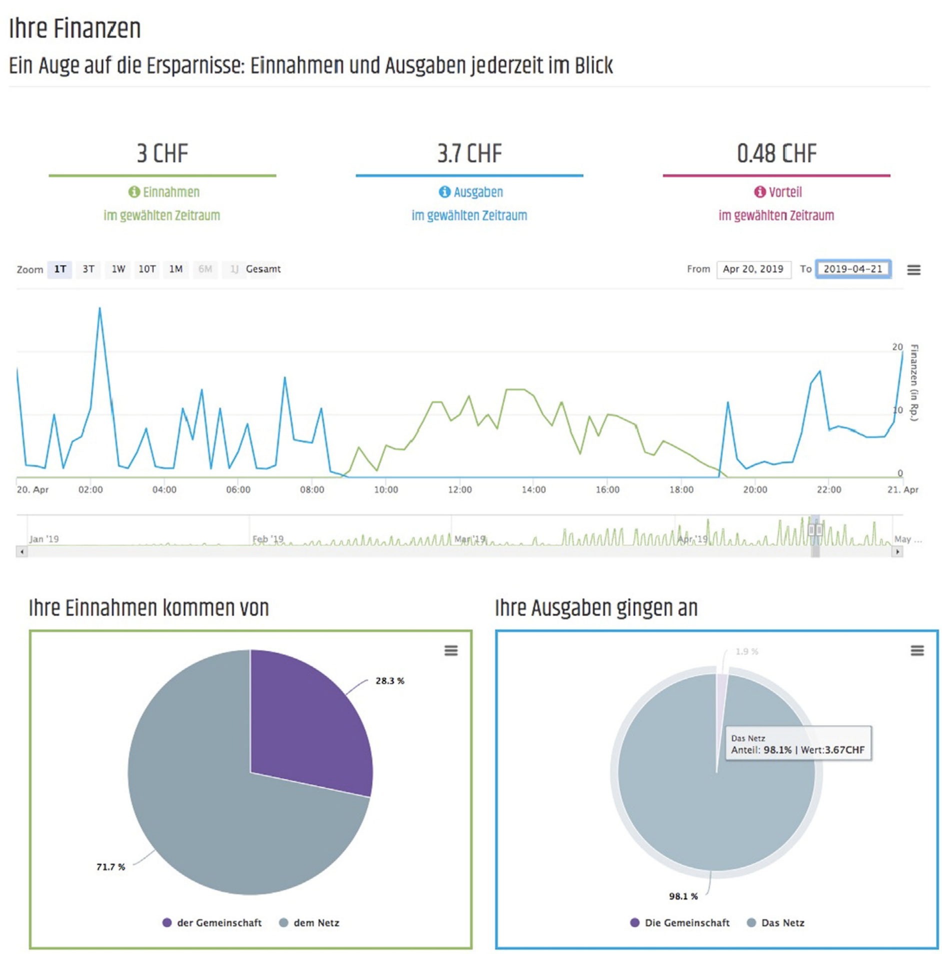
(2) Electricity Stock Exchange



(3) Community Electricity Data



(4) Financials



(5) Feedback Pop-ups

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