ICIS 2019 Proceedings

Sustainable and Societal Impact of IS

Peer-to-Peer Energy Trading in the Real World: Market Design and Evaluation of the User Value Proposition

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Wörner, Anselma; Ableitner, Liliane; Meeuw, Arne; Wortmann, Felix; and Tiefenbeck, Verena, "Peer-to-Peer Energy Trading in the Real World: Market Design and Evaluation of the User Value Proposition" (2019). *ICIS 2019 Proceedings*. 2.
https://aisel.aisnet.org/icis2019/sustainable_is/sustainable_is/2

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Completed Research Paper

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Abstract

Electricity markets are experiencing a shift to a more decentralized structure with small distributed renewable generation sources like residential photovoltaic systems. Simultaneously, information systems have driven the development of a "sharing economy" also in the electricity sector and can enable previously passive consumers to directly trade solar electricity in local communities. However, it is unclear how such peer-to-peer (P2P) markets should be designed to create value for the user. In a framed field experiment, we design and implement Switzerland's first real-world P2P electricity market in a local community. We examine its value proposition for the users and elicit user preferences by enabling the participants to directly influence buy and sell prices for local solar energy. The collected empirical evidence suggests that the P2P exchange is beneficial for users and provides incentives for generation of renewable energy. The results create valuable insights for the design and diffusion of future energy markets.

Keywords: Green IS, Smart Grid, Sharing Economy, Distributed Energy Resources, Peer-to-Peer Markets, Sustainability, Blockchain

Introduction

Renewable sources and distributed generation of wind and solar power play an increasingly important role in meeting future electricity demand and in reducing greenhouse gas emissions (Gholami et al. 2016; Ramchurn et al. 2012). Yet, the integration of distributed energy resources (DER) creates a challenge for the existing market structures (Koolen et al. 2017). Today's established power markets are strongly centralized and hierarchical with electricity distribution from a few power plants down to thousands of households. Wind and solar energy generation, in contrast, is geographically distributed, strongly volatile, and cannot be simply switched on or off according to the demand (Andoni et al. 2018; Ramchurn et al. 2012). Moreover, the novel, more active role of consumers who own solar panels and produce energy by themselves ("prosumers") creates challenges at different fronts, in particular for industry incumbents and traditional electricity markets.

Information technology can play a key role in this transformation of electricity markets, as it provides tools to control distributed networks and enable bidirectional communication with the user (Ramchurn et al. 2012; Seidel et al. 2017). Electronic markets and digital platforms have revolutionized a variety of industries by enabling a shift from traditional pipeline markets to P2P platforms, which now shape these industries (Van Alstyne et al. 2016). Information systems can provide personalized information (Tiefenbeck 2017) and create electronic marketplaces that can handle stochastic supply and demand in real time (Bichler et al. 2010; Gholami et al. 2016). Green IS research is thus in the ideal position to study innovative platforms which seize the possibilities of technological advances to market DER and foster sustainability among the broader public (Ketter et al. 2018; Seidel et al. 2017; Slavova and Constantinides 2017).

Recently, advances in distributed ledger technologies and the simultaneous decentralization of energy supply and have led to ambitions to create decentralized energy markets in which prosumers can directly sell excess renewable energy from peer to peer (Burger et al. 2016; Mengelkamp et al. 2017; Morstyn et al. 2018; Ramchurn et al. 2012). Using a digital platform, electricity from solar panels could be traded locally among neighbors within a microgrid, without a central utility provider serving as intermediary for these transactions. P2P energy markets have the potential to generate value on multiple levels: they allow for local matching of supply and demand for renewable energy, enable consumers to actively influence energy sourcing, and provide incentives for investments in renewable generation (Morstyn et al. 2018). Overall, this may reduce depletion of natural resources and greenhouse gas emissions in the long run, thus fostering sustainability (Andoni et al. 2018; Morstyn et al. 2018).

However, the performance of P2P energy markets has not been studied in practice yet. While there are several conceptual articles on decentralized energy markets (Andoni et al. 2018; Mengelkamp et al. 2017; Morstyn et al. 2018), empirical evidence for the feasibility and impact in the real world is still missing. This is not only due to the early stage of the technology or regulatory challenges. More importantly, like in other domains, energy trading on P2P markets implies a fundamental shift regarding the role of the participating citizens. This raises the question: Which value proposition do P2P markets create from the user perspective and to what extent are they an effective measure to empower once passive consumers to assume a more active role in these markets (Fridgen et al. 2018; Ketter et al. 2013; Morstyn et al. 2018)?

This paper presents a framed field study to explore the impact of P2P energy markets in the real world. More precisely, we have implemented a platform for trading solar energy among peers in a microgrid in Switzerland with 37 participating households. After an intensive period of selecting, developing, testing and deploying the information system, an active market phase with collection of trading data started in January 2019. Based on market design theory, we have designed a double auction mechanism to allocate solar energy and determine prices on this market. Each household explicitly states their willingness to pay for local solar energy and prosumers additionally define the conditions under which they are willing to sell energy produced by their solar panels. By analyzing the three-month dataset available, we examine energy matching, preference satisfaction and resulting benefits in a real-world instantiation of a P2P electricity market.

To the best of our knowledge, this article presents the first empirical evidence on a P2P electricity market in the field. Thus, we contribute early empirical research on a novel approach to tackle the energy transition using electronic markets, thus addressing one of the most pressing societal problems (United Nations 2019). By designing and implementing P2P trading in a local electricity market and by evaluating its impact from the user perspective, we go beyond the stage of merely conceptual or analytical research that characterizes the majority of research projects in the Green IS area (Gholami et al. 2016; Malhotra et al. 2013). We contribute to Green IS research and research on the sharing economy by testing an innovative solution concept to design electronic markets (Bichler et al. 2010) for fostering sustainability in the field (Seidel et al. 2017). In particular, we elicit real price preferences for local solar energy empirically in a real-world setting from the users' input to the market mechanism. These findings can serve as input to design local energy markets on a larger scale and possibly, to create personalized trading agents for electricity trading. The data thus provides meaningful information for policy makers to address the challenges of incorporating DER and to design future electricity markets. Furthermore, we provide empirical evidence for the user value proposition created on an electronic P2P market enabled by a distributed information system.

The remainder of this article is organized as follows. We first present existing literature on how information systems can support the creation of electronic markets for renewable energy and thus contribute to the transition to cleaner energy supply. We then describe the research design of our field study and the collected data, followed by an analysis of the data and a discussion of the empirical results in Sections 4 and 5. Finally, we summarize our contributions and propose future research avenues based on our findings.

Background and Related Work

Designing Smart Energy Markets

Different electronic peer-to-peer or "platform" markets which have emerged in recent years, have been subject to research both by economists and information systems scholars (Bichler et al. 2010; Slavova and Constantinides 2017). While market design is routed in economic theory, most new, emerging markets are enabled by computational tools and smart devices which in turn strongly influence the efficiency of and human interaction with these "smart markets" (Bichler et al. 2010; Zimmermann et al. 2018). The peer-to-peer exchange of goods and services on Airbnb, Uber and other sharing platforms represent economic systems, but these systems are strongly influenced by the information systems that support them (Glaser 2017; Lampinen and Brown 2017). This interdisciplinary nature makes smart markets a subject of interest for information systems research (Bichler et al. 2010; Melville 2010). As Lampinen and Brown (2017, p.1) put it : "Since markets are often instantiated in a technological form, we see an opportunity for our community to take an active role in designing markets and intervening critically where they do not work fairly or effectively.". Smart market design is concerned with the question how information systems can be leveraged to design well-functioning markets and how the user can be supported in the decision-making process without being overburdened with information (Bichler et al. 2010). Bichler et al. (2010) argue that the first step in designing smart markets is preference elicitation to understand and to model user behavior and preferences. The user perspective is necessary to make the right design choices on market mechanisms, input format and information provision. Furthermore, based on the user preferences elicited, real-time decision support systems can be created that adapt to the individual user and dynamic market conditions and that provide personalized recommendations. Herein, market designers should strive to align participants' incentives with the social goals respecting the specific characteristics and requirements of the domain (Ketter et al. 2013).

Energy markets represent some of the most information-intensive instantiations of markets due to the volatility in supply and demand and its dependency on environmental conditions (Koolen et al. 2017). Given that providing sustainable energy supply is one of the most critical societal tasks (United Nations 2015, 2019), several calls in recent years have encouraged research on Green IS and smart markets for sustainable energy (Gholami et al. 2016; Melville 2010; Seidel et al. 2017; Watson et al. 2010). Yet, the task of creating smarter energy markets is a wicked one, as the development of solution concepts viable in the real world involves engineering problems as well as active integration of the user (Seidel et al. 2017). Due to the complexity of impact-oriented Green IS research that examines the actual "'in-field' impact of such systems" (Malhotra et al. 2013, p. 1270) is very scarce (Gholami et al. 2016). Based on the assumption that energy is considered a homogeneous commodity, user preferences have been largely ignored in this sector for a long time.

P2P Energy Markets

In recent years, the energy market is undergoing substantial changes, not only on the physical, but also on the digital layer (Ketter et al. 2018). The massive deployment of smart meters in recent years has enabled monitoring the consumption of individual market participants in real time (Gholami et al. 2016). Information systems can further support algorithmic control within energy networks and bidirectional communication between consumers and prosumers, making it possible to implement a market mechanism that matches supply and demand based on real-time data and to provide decision support systems that individual consumers can interact with (Bichler et al. 2010; Ramchurn et al. 2012; Watson et al. 2010).

Consequently, new markets for DER are being developed by both academic scholars and industry research. One approach to better mirror the decentralization of energy supply in the energy market is to form local microgrids, i.e. electricity distribution systems which attempt to balance supply and demand on a local level (Brandt et al. 2014; Slavova and Constantinides 2017). Due to an increasing share of generation assets that is operated by private consumers and with the aim of creating a more consumer-centered market, the concept of P2P trading of local electricity in such microgrids has attracted interest among practitioners and scholars alike (Basden and Cottrell 2017; Mengelkamp et al. 2017; Wörner et al. 2019). P2P exchange of electricity signifies a paradigm shift to a decentralized bottom-up market in which individual consumers and prosumers can directly trade electricity on demand without the mediation of a central utility provider acting as reseller.

Morstyn et al. (2018) argue that, from the user perspective, the value proposition of P2P trading of renewable energy is threefold, p. 95: energy matching, preference satisfaction, and uncertainty reduction.

1. "Energy matching": The efficient coordination of supply and demand of energy requires a market mechanism that incorporates the specific characteristics of electricity as well as prosumer preferences. Ideally, the market mechanism incentivizes local production and storage capacities according to local demand in real time, thus reducing transactions with the central utility provider and required generation from centralized power plants (Ketter et al. 2013; Morstyn et al. 2018). Existing literature on P2P energy markets (Mengelkamp et al. 2018; Morstyn et al. 2018) mostly proposes some type of online, double auction as market mechanism, as market-based prices reflect supply and demand on a market in real time while allowing to engage the participant in the decision-making process at the same time.
2. "Preference satisfaction": Allowing consumers to state preferences on energy sourcing and different energy sources to be traded according to these preferences. Several studies (Capstick et al. 2015; Lee et al. 2015) as well as media reports (Aljazeera 2019; Economist 2019) suggest that in many countries public awareness for climate change and energy-related sustainability issues is rising. More and more individuals do not perceive electricity as a homogeneous commodity anymore and increasingly display preferences for local energy supply (Morstyn et al. 2018; Silva et al. 2012; Tabi et al. 2014). Hence, the integration of renewable energy drives more user-centric approaches (Andoni et al. 2018; Koolen et al. 2017). This trend is also reflected in recent statements of the European Consumer Organisation (2016) and the European Commission (2015), p. 1, who highlighted the need "to empower consumers through providing them with information, choice and through creating flexibility to manage demand as well as supply". In a choice experiment with consumers in Germany, Tabi et al. (2014) find that a large majority of consumers displays a preference for renewable energy supply and one quarter of them deem the location of electricity generation an important attribute. Likewise, results from an online survey by Ecker et al. (2018) suggest that consumers are willing to incur a price premium of 20% on average for renewable energy produced in their own homes. Yet, all these findings are based on self-reported survey data and an investigation of individual preferences and social behavior in a real market setting to develop efficient markets is still missing Andoni et al. (2018).
3. "Uncertainty reduction": As prices for residential photovoltaics systems have been falling over the past years, the number of small generators has been increasing. This has granted more and more consumers a new and more active role as "prosumers" who "both produce and consume electricity depending on their local requirements" (Ramchurn et al. 2012, p. 88) p. Yet, it is unclear for prosumers whether and how they can market energy produced from their generators in the long run: Recently, investments in renewable generation are highly uncertain, as subsidized feed-in-tariffs are declining or even abolished in many countries (Morstyn et al. 2018). Ideally, trading energy within a local P2P market increases revenues for prosumers and creates incentives for investments in renewable energy, hence reducing uncertainty of investments in DER. In turn, this may lead to investment spillovers (Bakos and Katsamakas 2008) increasing the adoption of renewable generators or smart load scheduling solutions as has been observed in P2P markets in other domains (Van Alstyne et al. 2016).

The Brooklyn Microgrid was the first running electricity exchange deployed in the field, in which locally produced energy from solar systems was sold within a neighborhood, and participants were directly involved in the trading (Mengelkamp et al. 2017). The Brooklyn Microgrid currently applies a uniform double auction (Lacity 2018; Mengelkamp et al. 2017), but so far, there is little information on the reasoning for the chosen market mechanism and there is no empirical data on the observed market outcomes available (yet). There are some simulation studies that examine individual aspects of peer-to-peer energy markets: In a simulation study based on load profiles from 4,190 households in Ireland, Griego et al. (2019) compare different compositions of load profiles for P2P microgrids. They find that communities of at least 10 households and a share of 40-60% perform best in terms of self-sufficiency rate (SSR), i.e. the share of energy consumption the microgrid can cover with local electricity production, and self-consumption rate (SCR), i.e. the share of locally produced electricity that can be consumed locally. Mengelkamp et al. (2018) conduct a simulation with load profiles from Germany, in which they implement a time-discrete double auction and use artificial bidding data. They find an overall SSR of max. 42%, but point out that the prices and allocation they find need to be validated with real field data on price preferences and bidding behavior. Block et al. (2007) design a combinatorial auction mechanism for electricity and heat trading in a microgrid, but provide no quantitative evaluation or field testing.

Several industry publications and whitepapers (Hasse et al. 2016; LO3 Energy 2017; Miller et al. 2017) present case studies with a stronger focus on the individual consumers. Yet, conceptual market designs presented in these publications are not empirically validated either. Moreover, these publications do not consider a market environment that allows users to actively take part in the pricing and allocation mechanism in the microgrid. To this date, there has not a been any real-world data reported on trading within a P2P energy market that provides empirical evidence to what extent the value propositions conjectured by Morstyn et al. (2018) and supported by other proponents of decentralized energy markets translate to the real world.

Energy auctions

The performance of a market depends on the interaction of the individual market participants with the market mechanism, on the input language and on the settlement process of triggered transactions (Ketter et al. 2013). Energy markets are complex multi-agent systems with diverse market participants exhibiting different individual preferences and trading strategies (Bichler et al. 2010; Ketter et al. 2013). Both supply and demand are volatile; to avoid blackouts, it is critical that supply and demand match at all times. Furthermore, electricity markets are vulnerable to strategic behavior, as participants have abundant opportunities for (implicit) collusion (Klemperer 2002). Consequently, the design of P2P energy markets – and electricity markets in general - needs to mitigate these risks and constraints adequately.

Most existing electricity markets and concepts for P2P energy markets employ an auction mechanism (Dauer et al. 2015; Koolen et al. 2017; Mengelkamp et al. 2017). This means that the participants express their preferences as bids containing a price and a quantity of electricity they want to purchase or sell. To balance supply and demand, all bids are collected in an order book and matched according to specific rules, similar to the operation of stock markets (Andoni et al. 2018; Fridgen et al. 2016). The rules of an auction have strategic implications on how the market participants formulate their bids to maximize their expected utility. Different types of auctions exhibit different properties such as: Pareto efficiency, which means that individuals with higher willingness to pay should be prioritized higher in the allocation of goods; incentive compatibility, which demands that agents' never have an incentive to misrepresent their true preferences in their bids; or the expected prices on the market (Mas-Colell et al. 1995). Regarding pricing rules, a main differentiation is whether prices are uniform (i.e. all bidders pay the same market clearing price) or discriminatory (i.e. bidders prices differ depending on their bids) (Fabra et al. 2002). Several studies show that discriminatory price auctions for electricity foster a more competitive environment; uniform price auctions, on the other hand, are more prone to collusive behavior on one side of the market (Fabra et al. 2002; Klemperer 2002). While a uniform price regime yields slightly lower average prices according to several studies based on simulations and lab experiments, discriminatory-price auctions can reduce volatility of prices (Rassenti et al. 2001). As market failure on a local electricity market may reduce efforts to create new, innovative market structures for the energy sector, it is crucial to study the design of electricity markets. The Californian electricity market in 2000 and 2001 serves as a negative real-world example that illustrates the potential real-world implications of a poor market design. During that period, the Californian market experienced tremendous volatility in prices and even some blackouts caused by poor auction design and strategic behavior of several market participants (including utility providers and generation plant operators), among other factors (Borenstein et al. 2002).

Method

Study Site and Setup

We have implemented a real-world microgrid in which prosumers can sell the (surplus) energy produced by their solar panels directly to consumers within their neighborhood using an auction mechanism. The study sample comprises 37 participants in a local municipality in Switzerland, 30 of which are prosumers who own (part of) a PV panel. Most of the participants are private households, with the exception of one flower shop and one nursery home for elderly people with approximately 50 residents.[1] All participants are customers of the local utility provider (blinded for review), whose support and active role has been vital to the launch and success of the project. Together with the academic researchers, they selected and recruited the participants from a neighborhood with a high penetration of residential PV panels and served as a trusted local point of contact.

The research team deployed smart meters, which measure electricity loads in time intervals of 15 minutes, in every participating household. Each household received one device that measures electricity consumption. Prosumers received another smart meter for measuring electricity production from their PV panels and participants who own a battery storage system received a third smart meter for measuring battery loads. Altogether, the research team installed 75 smart meters in the participating households; all devices are connected to the internet.

Design and Implementation of the Market Mechanism

Based on experimental and simulation studies on auction mechanisms for electricity trading (Klemperer 2002; Nicolaisen et al. 2001; Rassenti et al. 2003; Rosen and Madlener 2013), we have implemented a market mechanism for P2P trading in our market that takes into account the specific setting of P2P exchange between private households: a time-discrete, discriminative double auction. We identified a double auction as the most suitable archetype of an auction mechanism for the present setting to enable prosumers as well as consumers to decide for which conditions they are willing to sell or buy sustainable electricity (Rosen and Madlener 2013). This double auction takes the prices defined by the participants, as well as their consumption and production loads measured by the smart meters as input. Due to the propensity of electricity markets for collusive behavior described above, discriminatory pricing seemed more advantageous than uniform pricing (Klemperer 2002). In addition, the limited volatility observed for discriminatory pricing (Rassenti et al. 2003) is critical to provide affordable and calculable costs for energy supply and not to alienate households taking part in energy trading for the first time (Rosen and Madlener 2013). Although prices are expected to be slightly higher in a discriminatory auction than with a uniform pricing scheme (Fabra et al. 2002; Rassenti et al. 2003), this is not necessarily a disadvantage in the local electricity exchange, as it benefits the prosumers generating renewable energy and may thus foster the profitability and diffusion of DER. Moreover, related literature has shown that many consumers state that they are willing to incur higher costs for renewable or local energy (Ecker et al. 2018; Tabi et al. 2014).

The participants' buy and sell orders for local electricity are collected over a "clearing period" of 15 minutes. After the orders are collected, the auction mechanism is run to clear the market and determine the resulting electricity trades. The discriminative double auction matches the highest buy order with the lowest sell order (in terms of price) and progresses like this through the entire order book. The price for each matched trade is the mean between the sell and the buy price of the respective orders ("discriminative/midpoint pricing"). A sample orderbook is depicted in Figure 1: The blue and green curve show buy and sell orders, respectively. The dashed grey line indicates the realized prices resulting from the auction mechanism.

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[1] For simplicity reasons, we will refer to "participating households"/ "participants" in the remainder of this article and include the flower shop and the nursery home in this terminology.

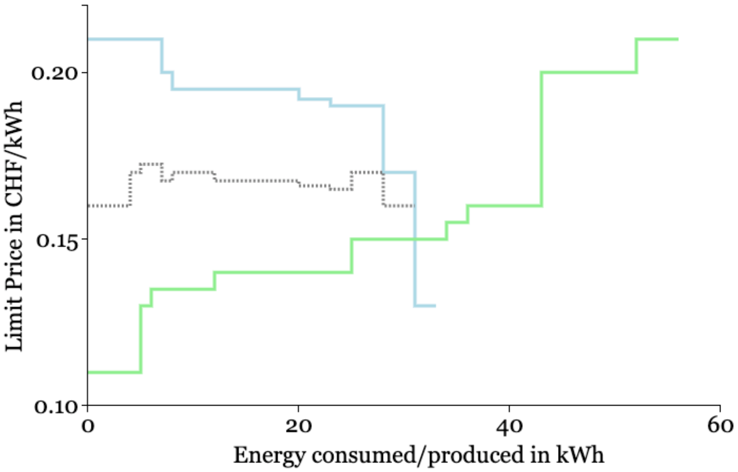
SELL orders		
Address	Volume	Min. Sell Price[2]
53ae...	5 kWh	0.11 CHF/kWh
2c35...	1 kWh	0.13 CHF/kWh

...

BUY orders		
Address	Volume	Max. Buy Price
327e...	7 kWh	0.21 CHF/kWh
9d1f...	2 kWh	0.20 CHF/kWh

...

a)



b)

Figure 1. a) Extracts from a sample orderbook, containing energy loads and prices b) chart of a sample order book of one time slot during the day.

As electricity supply and demand need to be balanced at all times, the local utility provider serves as backup for the microgrid: When there is not enough solar energy in the local market, or when there is more production than demand within the local market, the local utility provider covers (and absorbs, respectively) these undersupplied (and excess, respectively) capacities at its standard tariffs. In the study location, the standard electricity tariff incurred by residential consumers is 0.2075 CHF/kWh and the feed-in-tariff for local production that is fed back into the grid is 0.0979 CHF/kWh (including network charges that have to be reimbursed to the utility company).

Design and Implementation of the P2P Trading Platform

The software enabling the P2P trading and communication within the microgrid is running in a decentralized manner on smart meters. Each of the participating households was equipped with a smart meter (a Raspberry Pi with expansion modules to measure voltage and current) which ran a permissioned blockchain system based on the Tendermint consensus protocol (Kwon 2014) (an overview of the system is provided in Figure 2). The auction mechanism was implemented on the application layer of this blockchain and is running as a smart contract without using a central server. All bids were handled in a pseudo-anonymous way, as each smart meter received an address which only the research team knew. Hence, participants did not know with which of their neighbors they were trading electricity with, or who asked for which price. More details on the technical details of the system architecture are available in the technical report (Ableitner et al. 2019).

In order to encourage an active participation of the households and to elicit their price preferences (Bichler et al. 2010) regarding local solar energy, the participants received access to a personalized web application for the P2P trading. The application allows them to monitor real-time data on their energy consumption (and production, if applicable), on their past trading behavior and, in particular, to place price bids: By moving a slider element, they can state their willingness to pay for solar electricity produced by their neighbors in the microgrid (Ableitner et al. 2019). Prosumers can further define their minimum ask price for selling energy from their solar panels to their neighbors. The participants are free to define their price bids just once or adjust them as often as they wish. The application provided them with a concise overview of their energy data and their trading outcomes on the local market in real-time at their discretion, as earlier research indicates that participants may be interested in the local origin of the energy they buy (Ecker et al. 2018; Meeuw et al. 2018). (Note that the details on the development of the user interface and analyses related to user experience and system usage are beyond the scope of this manuscript.)

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[2] CHF=Swiss Francs

While in theory, the participants have the possibility to adjust their maximum buy and minimum sell price as often as they want, the research team did, obviously, not expect them to continuously monitor the auction execution or to take action on a daily or (sub)hourly basis. Once they have set their price bids in the web application, orders are posted by the smart meters every 15 minutes. The auction is executed every 15 minutes to clear the market so that prices reflect availability of solar energy in near real time (Rosen and Madlener 2013). Participants received a monthly report summarizing the information available on the web application. It included their energy consumption and production, resulting expenses, share of local energy supply and the average price they incurred for local energy. The report was sent out at the end of each month via email.

A key feature that sets this field study apart from prior research is that the participants are in fact charged according to the prices defined by the participants on the P2P market and that the electricity trades computed by the described auction mechanism occur in reality. Consequently, the price preferences we elicit from the participants are not merely responses to a hypothetical scenario in a survey, but they influence the actual electricity costs participants incur. Participants have been made aware of this fact in an information event prior to the study (attended by 29 out of 37 households) and all participants have signed a letter of consent in advance.

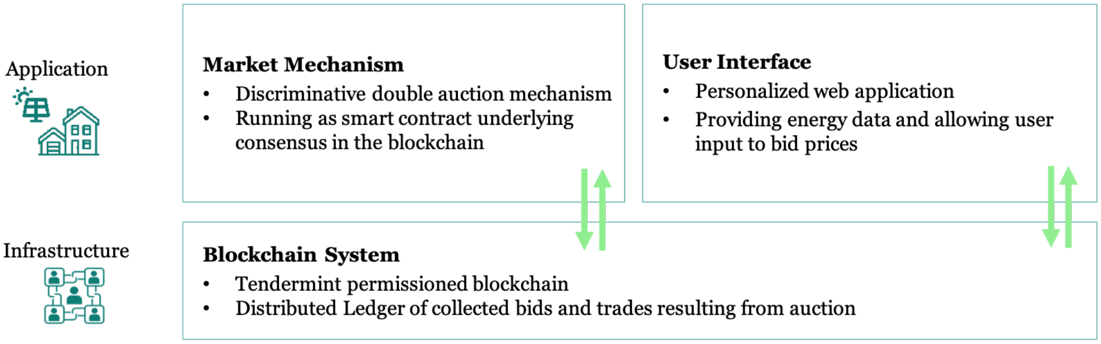

Figure 2. Schematic representation of the main system components of the P2P trading platform: blockchain infrastructure, market mechanism, and user interface

Data Collection and Analyses

We collect data in the P2P microgrid described above for a duration of three months, from January 7, 2019 to March 31, 2019. In addition to the trading data, we have also conducted a pre-experimental survey to gather supplementary information on participants' preferences and their socio-demographics. The study sample comprises 37 participating households, including 30 prosumer households. The prosumers' total peak production capacity exceeds 280 kWp. Over the duration of the study, the solar panels have produced 48,981 kWh and the participating households have consumed a total of 130,378 kWh. Over the study period of three months (8,024 clearing periods), we observed a total of 292,316 orders posted in our microgrid. The time-discrete, discriminative double auction we have implemented matched 424,049 trades from these orders, which were stored on the blockchain.

Based on this data, this paper examines to what extent the implemented market realizes the value propositions laid out by Morstyn et al. (2018). To that end, we analyze the energy allocation and market efficiency achieved during the study period of three months, and examine the preferences elicited in form of prices bid by the participants. Furthermore, we analyze realized prices and resulting savings and revenues for consumers and prosumers, respectively as performance indicators of the market. We report most results as relative values, as the absolute values depend strongly on absolute prices of the local utility provider and the absolute energy demand and production in the specific microgrid.

Results

Based on the data collected, we analyze the efficiency of the P2P market, participants' price preferences, and realized prices for local electricity to empirically evaluate the value proposition of P2P trading from the user perspective along the three dimensions described by Morstyn et al. (2018).

Energy Matching

To evaluate the efficient coordination of supply and demand in the P2P market, we examine how energy was allocated within the microgrid. More precisely, we investigate whether the P2P market for solar energy provided incentives for renewable energy consumption and production and led to energy matching on a local level. Figure 3 depicts the weighted mean price to pay for energy by members of the microgrid. The green line depicts the average day from the study period of January to March, the light green line the day with most solar production and the light blue line the day with least solar energy. As the chart illustrates, the price for energy decreases over the course of each day when orders could be matched, depending on the availability of solar energy and demand within the microgrid (green bars depict solar production, blue bars consumption). This type of price curve was also observed in related simulations (Mengelkamp et al. 2018). The fact that the market price represents the relation of supply and demand in this way is desirable, as it incentivizes electricity consumption when there is most renewable production and highlights the very idea of a functioning market (Ketter et al. 2013). The lowest average market price was achieved at middays on the sunniest days of the study period. In almost all clearing periods, average prices were between the feed-in tariff (0.979 CHF/kWh) and the residential retail tariff (0.2075 CHF/kWh), except for very few periods, in which consumers paid a price premium for local energy.

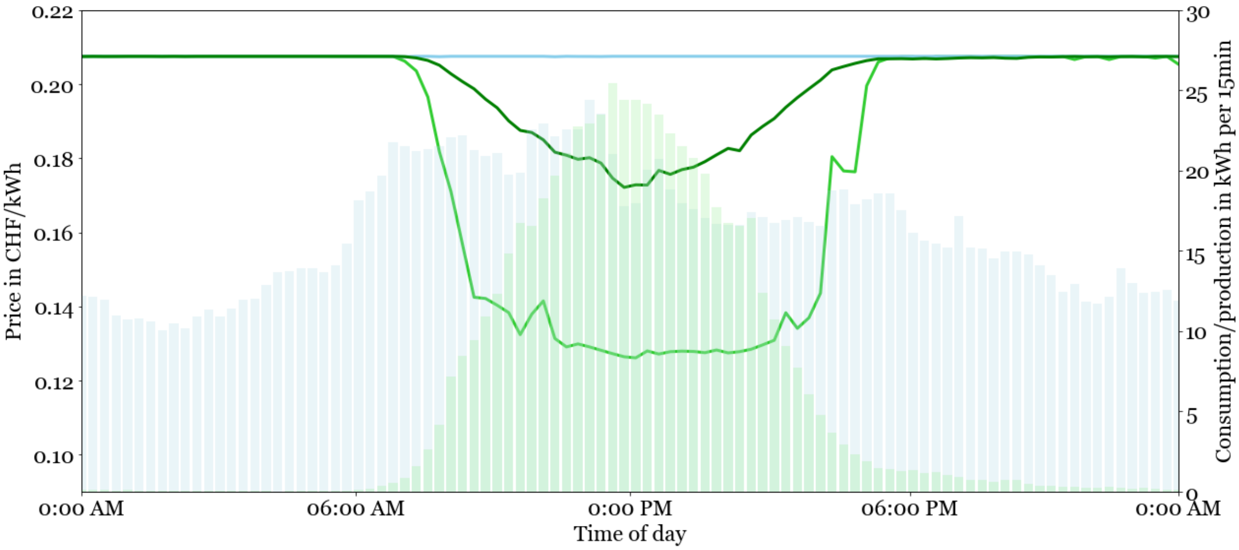

Figure 3. Price evolution over time of day during the three-month study period in winter: average day (dark green line graph), sunniest day (light green line), least sunny day (light blue line). The bar chart depicts average production and consumption loads in kWh. Prices within the P2P exchange reflect availability of local energy and range between feed-in and residential retail tariff.

The influence of sunny hours on the average energy price depicted in Figure 3 within the microgrid indicates that a considerable share of energy was indeed traded among peers and not at the fixed tariff defined by the utility provider (0.2075 CHF/kWh). As all participating households are located within the same neighborhood, consumption profiles – and even more so production profiles – exhibit a high correlation between households (Griego et al. 2019). Given that, it is striking to what extent the local P2P trading increased local consumption of solar production (Figure 4): Without P2P trading, the overall SSR at microgrid level corresponds to the share of electricity demand covered by the prosumers consuming their own solar energy. Over the duration of the study, the microgrid's SSR without P2P trading would have been 15.5%. With the P2P trading system enabled, the microgrid's SSR almost doubled to 26.3%. Similarly, in the absence of P2P trading, the SCR, i.e. the share of produced solar energy that is consumed by the prosumers in their own houses, would have been 41.2% over the duration of the study. With the P2P trading system, the SCR of the microgrid increased to 70.0%. These results are remarkable given that we considered three winter months in a microgrid with a higher prosumer share than recommended in Griego et al. (2019) and assumed in Mengelkamp et al. (2018). Overall, by enabling P2P trading, transactions of 14,092 kWh that would normally have involved the utility company were replaced by transactions among households within the microgrid (light green slices in Figure 4). This implies that the load profiles and preferences stated by the participants could be matched for transactions of this volume.

To get an understanding of the efficiency of the market, we will now compare this volume to the volume of energy that could have mathematically been traded within the microgrid given local supply and demand – in other words, the local solar production that occurred simultaneously with consumption within the microgrid. We find that local supply and demand actually concurred for 16,439 kWh and could thus technically have been matched within the microgrid. This means that during the three-month period of the study, 2,347 kWh of locally produced solar energy were not sold within the microgrid although there was local demand for it, due to a mismatch in participants' bid prices. Since orders which cannot be filled within the P2P market have to be settled with the utility provider in any case, these transactions represent an inefficiency. If participants' price bids had not been taken into account, the SSR of the microgrid would have been 1.8 percentage points higher (i.e., 12.6% of energy consumed could have been bought from the local microgrid instead of 10.8%); yet, that fraction was supplied by the utility company. The freedom of decision-making granted to the participants by actively including them in the pricing process thus comes at a trade-off of this decrease in SSR.

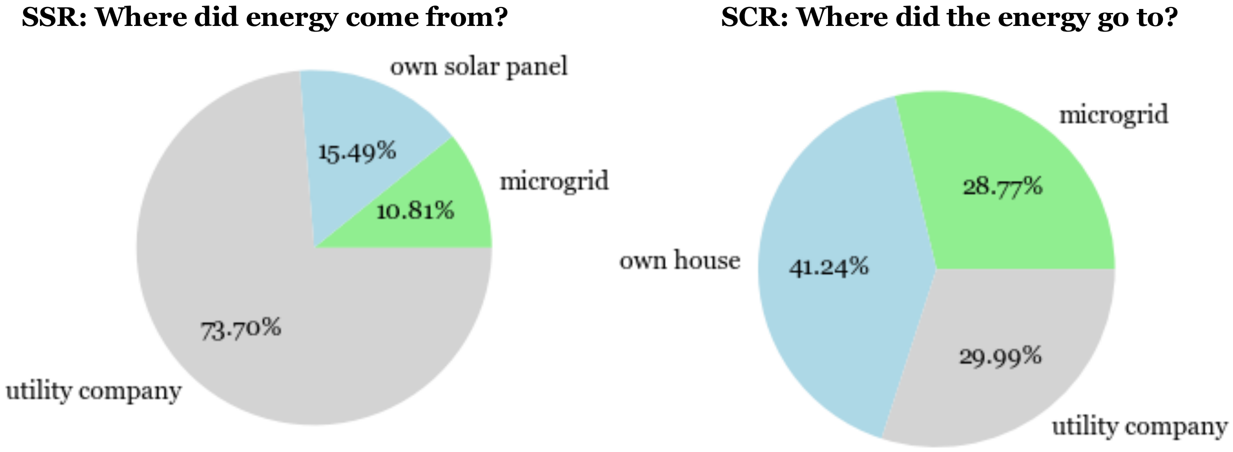

Figure 4. Energy allocation. Self-sufficiency rate of the microgrid reaches 26.3%, and self-consumption rate 70.0% (sum of blue & green slices in both diagrams).

Preference Satisfaction

To evaluate price preferences for local electricity and their satisfaction on the P2P market, we compare preferences stated in the pre-experimental survey to prices bid in the market setting. As a first step, we asked participants prior to the field experiment whether they would be willing to incur higher costs for solar energy or for local energy supply: In this survey, 13 out of 31 participants who filled out the survey stated that they were willing to incur a price premium for *solar* energy and 17 that they would for *local* energy.

As a second step, we analyze the prices bid by the participants in the market environment to examine individual preferences stated on the market: The histogram in Figure 5 displays all bids made on the P2P market. These bids reveal several interesting insights on the preferences elicited from the study participants. First, 27 of the 37 participants chose to define price bids other than the default prices, at least at some point during the study which indicates their willingness to engage on the market. Consumers offered 0.1923 CHF/kWH (sd=2.37) on average for solar energy. The average sell price that prosumer wanted to earn was 0.1367 CHF (sd=3.85). This implies that in general, many transactions among the peers can be matched within the microgrid. However, a lot of buy prices as well as sell prices bid intersect in the interval between 0.125 and 0.18 CHF/kWh. This indicates that there may occur cases in which sell orders ask for a higher price than offered in the buy orders – which explains the inefficiencies identified above. Moreover, the high standard deviation and broad distribution of bids indicates that participants have heterogeneous preferences and that many participants did seize the opportunity to influence the decision making process on the market.

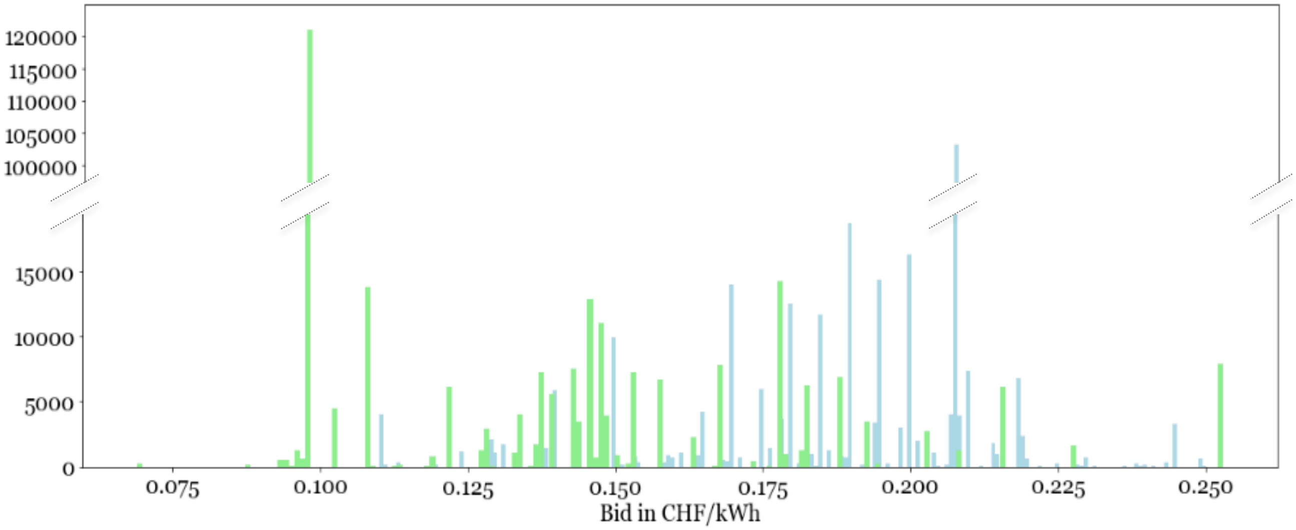

Figure 5. Histogram of prices bid for local solar energy: Sell prices bid are displayed in green, buy prices bid in blue (default tariffs defined by the utility provider: 0.0979 CHF/kWh and 0.2075 kWh).

While we observe that some prosumers asked a price premium be paid by the consumers (sell bids >0.2075 CHF/kWh), none of them is willing to incur opportunity costs for selling their energy locally by offering their solar energy below the feed-in tariff (< 0.0979 CHF/kWh). Hence, the bids by prosumers in this study do not display other-regarding preferences or prosocial behavior for selling electricity locally. On the consumer side, 11% of the buy orders are higher than the utility tariff; these orders were posted by 6 different participants. While these 6 participants (temporarily) offered to incur a slight price premium for solar energy from the microgrid, overall, the participants' real-world price settings in the field study considerably deviate from their self-reported preferences indicated in the pre-experimental survey. In other words, once their choices were consequential for their real-world income, they were less willing to pay a price premium for local solar energy (and to incur opportunity costs for selling their energy locally, respectively) than their responses to the hypothetical scenario in the survey prior to the field study had suggested. These findings call into question the results of survey-based evaluations of individuals' willingness to pay for renewable energies (Ecker et al. 2018; Tabi et al. 2014). Participants' self-reported inclination towards renewable and local energy (as stated in our pre-experimental survey), which is in line with preferences reported by other survey-based studies in the existing literature, does not translate into their behavior in the market setting in which participants' bids determine the actual costs they incur.

Uncertainty Reduction

Having examined the preferences elicited, we now turn to the prices realized to examine to what extent P2P trading may help to reduce uncertainty for the prosumers (Morstyn et al. 2018). To that end, we assess the transactions realized and their implications for the users. The mean price per kWh for transactions among peers is 0.1680 CHF (sd 1.78 CHF). Except for a few cases, prices for almost all transactions fall within the limits of the fixed feed-in tariff of 0.0979 CHF (as lower bound) and the residential retail tariff 0.2075 CHF (as upper bound). As illustrated in Figure 3, prices for local solar energy vary over the course of the day, depending on the availability of solar energy. This has two implications, both of which are in line with the results above: 1) On average, both sellers and buyers benefit from the P2P transaction, as they trade at a price that is below the price that the consumer would have to pay to the utility company and above the revenue that the prosumer would earn for feeding into the grid. 2) The average prices realized do not include a price premium over the grid tariffs.

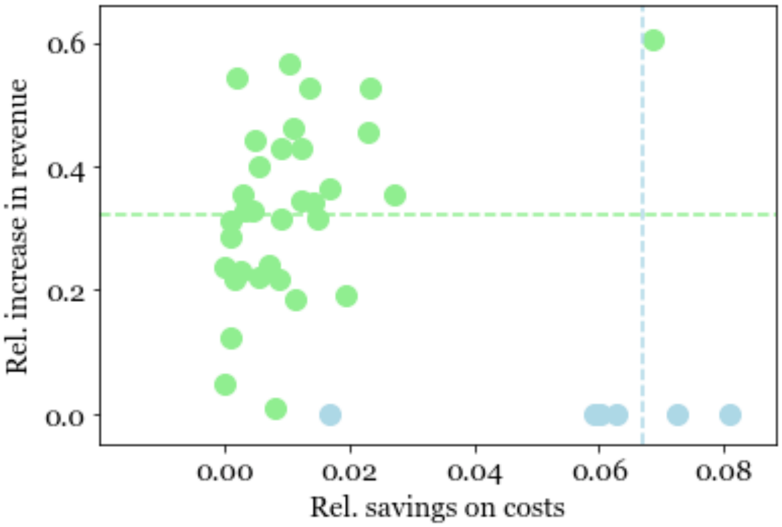

Figure 6. Savings and additional revenue incurred by each participant in the P2P market relative to their expenses/revenue for trading electricity with traditional tariffs.

In fact, we find that all users have benefited from the P2P trading in the field study: We compare their incurred electricity costs in the P2P market with the costs users would have incurred if they had not been part of the microgrid and if they had bought from and sold to the electricity provider. Summing up the transactions for each user in this way, each of the participants either saves electricity costs, earns more for the solar electricity she produces, or both. The scatter plot in Figure 6 shows the relative increase in revenues for sold electricity (on the y-axis) and relative savings on electricity expenses (on the x-axis) by each of the users. Pure consumers are depicted in blue (no electricity sold, hence no revenue increase), prosumers in green. On average, users earned 32.2% (sd=0.15) more for the electricity they sell, and saved 1.8% (sd=0.022) of their electricity expenses. At first glance, the relative savings on electricity purchased seem very small. Upon closer inspection, the numbers are not surprising, as prosumers cannot save much in buying solar energy, as they mostly consume solar energy from their own roofs during sunny hours– they benefit from the peer-to-peer market on the seller side. If we focus on pure consumers alone (who do not own a solar panel), they saved an average of 6.7% (sd=0.008) of their electricity bill. Moreover, we expect savings to increase in summer months with more excess supply and prolonged hours of sunlight. Taken together, the results indicate that the market design is supporting the overall goal of providing a profitable market for renewable energy produced by small prosumers and reducing uncertainty for prosumers' investments.

Discussion & Conclusion

Discussion

This paper investigates a P2P market for solar energy in the field and collects high-resolution empirical data in a microgrid of 37 participating households over the duration of three months. The paper thus contributes to the discussion on smart markets for renewable energy (Bichler et al. 2010; Ketter et al. 2018) and green IS (Gholami et al. 2016; Malhotra et al. 2013; Melville 2010). To the best of our knowledge, this is the first scientific evidence on trading conducted on a P2P energy market in the real world. We examine the data collected with respect to the three value propositions of P2P trading proposed by Morstyn et al. (2018): energy matching, preference satisfaction, and uncertainty reduction. It is important to note that we do not claim that the quantitative results we achieve in our study sample are generalizable to the broader public. Given the novelty of this research area and the complexity of the energy market (Ketter et al. 2013), we examine the value propositions of peer-to-peer markets that have been theorized in the literature in the field and provide a first benchmark for the real-world impact of peer-to-peer energy trading among users in the field. With this impact-oriented approach (Gholami et al. 2016), we tackle the first stage of smart market design of understanding the user value and eliciting user preferences, as described in Bichler et al. (2010).

Despite the local proximity of the participating households, our findings indicate that by matching supply and demand within the P2P market, the share of self-sufficiency of the microgrid can be increased by 70% (from SSR of 15.5% to 26.3%), even during the winter months of January to March. We expect these figures to increase over the summer months with longer hours of sunlight. Moreover, given that prosumers still sell around one third of the solar energy to the utility provider, SSR and SCR could be increased by shifting flexible loads or by deploying more storage capacities in the microgrid. The double auction employs price limits stated by the users to match trades. Yet, there is a tradeoff between computing an efficient energy matching on the one hand, and on the other hand enabling individual preference satisfaction (Morstyn et al. 2018) of the users by letting them bid prices: Energy that cannot be matched on the P2P market needs to be supplied from the utility provider at the residential retail tariff, as security of supply needs to be guaranteed at any time. The inefficiency we observe in this field study reduced the technically possible SSR by 1.8% percentage points - with a decreasing tendency over time. This seems like an acceptable tradeoff; in exchange, the market design implemented in this study allowed a greater influence of the participants, as they could directly state their willingness to pay for local solar power and thus actively influence prices. Aside from that, the real-time prices achieved in the market reflect the relation of supply and demand on the market very well, as is shown in Figure 3. The pricing achieved by the matching mechanism selected thus also incentivizes shifting consumption loads to periods in which local solar energy is available, which could be achieved using smart appliances or storage capacities in the future (Fridgen et al. 2016). This result is also interesting beyond the context of the energy domain, as it shows that with the right market design, a P2P market can be relatively efficient while, at the same time, enabling individuals to participate in the decision making on a market (Lampinen and Brown 2017). The double auction mechanism can handle manually defined, heterogeneous individual preferences and still run autonomously in real-time.

Furthermore, in our field study, the vast majority of residential solar energy was sold within the P2P market and increased revenues from renewable generation, thus reducing uncertainty of returns on investments for prosumers. As argued above, the auction mechanism manages to provide incentives for local generation, which in turn creates incentives for investments in renewable generation and reduces insecurity of investment. It is important to note that the feed-in tariff granted in this field study is relatively low compared to current, subsidized tariffs in European countries. However, this projects the future market structure, as feed-in tariffs and their financial support schemes have been reduced in the past years and might even disappear in some countries (Karneyeva and Wüstenhagen 2017), which illustrates the importance of studying novel market structures integrating distributed prosumers.

Regarding the preferences displayed by the participants of our field study, our findings challenge the findings of existing surveys regarding individuals' willingness to pay for renewable energy (Ecker et al. 2018; Tabi et al. 2014). In line with prior survey-based studies, our participants had stated a high willingness to pay for local energy from the P2P market in the pre-experimental survey. However, their subsequent actual bids in the field study were substantially lower and did not reflect strong preferences (in form of a price premium) for local solar energy over energy supplied by the utility provider. The direct preference elicitation from the consumers (by letting them bid a price per kWh of solar energy) may seem like an extreme approach to involve the user in a rather abstract decision making process. Nevertheless, the results indicate that direct involvement of consumers is indeed crucial to understand the heterogeneity of preference profiles and consumer behavior in a real market environment, as this may differ strongly from their statements made in surveys. Moreover, there may be additional societal benefits of engaging consumers directly in the energy market (European Consumer Organisation 2016): By allowing consumers to influence the energy sources they use or even the prices they pay, they assume a more active role. We conjecture that this empowerment may increase the salience and the understanding of energy supply. We took an extreme approach that directly allowed the users to bid prices for different sources of energy. The results can now serve as empirical starting point for designing decision support systems which automatize smart trading strategies adapting to the consumer type (Bichler et al. 2010) or which provide consumer analytics for energy consumption. Also beyond the energy sector, information systems provide various avenues to support users in decision processes both in their professional and private lives. Many of these systems include autonomous agents and regardless of the specific application context (Bichler et al. 2010; Gholami et al. 2016), a key question will be how to make sure that these systems act according to the users' preferences. The discrepancy between the participants' self-reported price preferences in a hypothetical scenario and their actual price settings in the field study highlight the importance of empirical research to better align the strategies of autonomous agents with the individuals' actual preferences in the real world.

Overall, our results confirm the value propositions of P2P markets that were theorized in the related literature (Andoni et al. 2018; Mengelkamp et al. 2017; Morstyn et al. 2018) and have, partially, been observed in electronic peer-to-peer markets in other domains (Einav et al. 2016; Zimmermann et al. 2018). Trading energy directly between private households may become part of a future energy landscape, since our field study shows that the technology to put such platforms into practice already exists. Yet, future research needs to investigate whether these benefits are actually perceived and appreciated by the individual user and whether they justify the costs, time, and efforts involved in the deployment of a distributed information system. With this paper, we take a step to address the dearth of impact-oriented research in the field of green IS (Gholami et al. 2016); yet, fostering sustainability is a wicked problem with many interrelated aspects and consequently, the design of smart energy markets for the future will require further research.

Limitations & Outlook

Despite the best of our efforts, this study is not without limitations. The very complex technical setting in the field and the criticality of energy supply for all users imposes some natural restrictions to the study design. Due to the complexity of the study implementation, the explorative approach on a critical infrastructure, and to the associated costs, the sample was limited to 37 participating households. Furthermore, the sample recruited features a high share of prosumers; as early adopters, they may be more interested in energy or sustainability topics than the general public, therefore the results may be subject to volunteer selection bias (Tiefenbeck et al. 2019). Future research needs to investigate to what extent a broader population is receptive to P2P energy markets and how these markets and the user interfaces need to be designed not to overwhelm citizens who so far did not have any active role in the electricity market. This being said, it is all the more remarkable that in the field study, we cannot replicate the high willingness to pay for local solar power which the same participants had stated in our pre-experimental survey and which is in line with previous survey-based studies (Ecker et al. 2018; Tabi et al. 2014).

From an economic perspective, a particular feature of the application context is that the utility provider backs up every order that could not be matched within the microgrid. If that was not the case, the strategic incentives in the market would have been reduced and Pareto efficiency would have been fulfilled. However, it is a necessity to keep the electricity grid in balance and to provide reliable electricity supply at all times, so the tradeoff between respecting individual preferences and accepting inefficiencies is a natural property of market design in this domain.

One reason for the lack of empirical data on P2P electricity trading is that technological advances in communication technology and distributed ledger technologies have spurred the interest in decentralized platforms only in recent years (Albrecht et al. n.d.; Basden and Cottrell 2017; Buterin 2014; Hasse et al. 2016; Mengelkamp et al. 2018). Naturally, the field implementation of such a complex socio-technical system raises various interesting questions in different research areas, including human-computer interaction, technical aspects, and regulatory issues. For instance, the choice of the technical system architecture is beyond the scope of the present article. In particular, we do not aim to evaluate the advantages or disadvantages of the blockchain infrastructure implemented in the field test in this article. Another aspect requiring further investigation relates to the design choices of the user interface implemented on this P2P market and its influence on the trading behavior and understanding of the users. In the course of the research project, we will implement several interventions and will collect qualitative data to assess these questions in detail. Going forward, it would be also interesting to investigate other market designs incorporating forecasts and include decision support systems for the user (Bichler et al. 2010), e.g. active control of flexible loads and storage capacities, or autonomous agents taking part in the auction mechanism based on user input. For that purpose, it would be interesting to examine spillover effects on renewable adoption and possible shifts in load profiles caused by the real-time pricing and additional information provided to the users. Such effects have been observed in other studies on P2P platforms (Bakos and Katsamakas 2008). Finally, the deployment of P2P energy markets on a larger scale will have implications on the grid infrastructure, grid costs, and demand schedules which need to be carefully investigated from an engineering perspective on a systemic level. In this context, an obvious question relates to alternative models for grid fees and pricing schemes to recover the costs for (super)regional transmission lines if the diffusion of P2P markets picks up and consequently, the share of locally produced and consumed energy increases ("Who pays for the grid?"). In sum, while we cannot address the variety and breath of important questions arising in detail in this article, the empirical data collected provide a concrete starting point to foster the debate across disciplines.

Conclusion

In recent years, advances in personal information systems and in blockchain technology have enabled the creation of new marketplaces, in particular for trading or sharing of goods among private consumers. Given the increase of distributed energy resources, the energy sector can benefit from this evolution if a market design can be established that is beneficial to the user (Bichler et al. 2010; Morstyn et al. 2018). We conduct a framed field study to test a P2P energy market in the real world and present early empirical evidence on the impact of this novel market platform from the user perspective. To that end, we set up a P2P electricity exchange for solar energy in a local microgrid in Switzerland. Based on existing literature on P2P energy markets and market design theory, we implemented a time-discrete, iterative double auction with discriminative pricing. We benchmark the trading data observed in the field study against the established utility pricing. Furthermore, we compare the preferences displayed by the users on the real-world market to survey-based findings on consumer preferences for local or solar energy, both elicited from the same participants, and reported in prior literature. Our results suggest that the value propositions theorized in the literature can actually be realized for the user in P2P energy markets. If the regulatory framework allows, information systems can be a viable option for prosumers to sell their excess production locally and directly instead of being dependent on feed-in tariffs determined by regulators and utility companies. Furthermore, we find that caution is warranted in relying on survey data on consumer preferences regarding renewable or local energy supply. We suggest to facilitate the creation of user-centric market structures that allow for local energy matching and provide the possibility to reflect heterogeneous consumer profiles. When addressing the user needs and employing efficient market mechanisms, information systems have the potential to create smart energy markets that foster sustainability on its three levels: socially, economically, and ecologically.

Acknowledgements

This research project is supported within the flagship program by the Swiss Federal Office of Energy.

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