An HCI Perspective on Distributed Ledger Technologies for Peer-to-Peer Energy Trading

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Abstract. Distributed Ledger Technologies (DLT), such as blockchain, are gaining increasing attention in the energy sector, where they can be used to support Peer-to-Peer (P2P) energy trading. Several proof-of-concept and pilot projects are running all over the world to test this specific use case. However, despite much work addressing the technical and regulatory aspects related to DLT for P2P energy trading, our understanding of the human aspects affecting the adoption of these systems and technologies is still minimal.

The development of a decentralized energy market poses interesting challenges to the HCI community and raises important questions that need to be answered: do people trust a system which is, by definition, trust-free? How do they perceive P2P energy trading? What are their needs and motivations for engaging in energy trading? Moreover, are people willing to use cryptocurrencies as a medium of exchange for energy? And, to what extent is full-automation desirable?

To shed light on these and related questions, we developed and tested *PowerShare*, a decentralized, P2P energy trading platform. In this paper, we report on our findings from interviews with nine families that have used *PowerShare* for a month. Motivated by our empirical findings we conclude by highlighting guidelines for designing P2P energy trading platforms and elaborate directions for further research.

Keywords: Human Computer Interaction · Peer-to-Peer Networks · Sustainable HCI · Distributed Ledger Technologies · Energy trading

1 Introduction

Energy has become established as an essential topic of interest for Human-Computer Interaction (HCI) research, particularly concerning the area of sustainable HCI [1, 2]. While most of the research focuses on Eco-feedback technologies (i.e. the technology providing feedback on behaviors with a goal of reducing environmental impact), others have also looked at how energy is an intricate design concept (i.e., both an immaterial concept but also a commodified and usable resource) [3]. However, little HCI research focused on changing energy infrastructures, which represents an increasingly relevant

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topic in the face of climate action. Modern energy production and distribution infrastructures are facing exceptional challenges: from the limited ability to accommodate low carbon generation (intrinsically invariable and hard to predict) to the electrification of important heat and transport sectors (leading to energy peaks that are disproportionately higher than the existing trends).

In this paper, we build on the state of the art by looking at changes in energy at the infrastructure level. We do this by looking at how new Peer-to-Peer (P2P) and microgrid technologies are radically changing the days when energy was centrally produced in large power plants and then distributed to our homes as a commodity. People are increasingly installing solar photovoltaic (PV) panels – i.e. panel modules composed of photovoltaic cells, made from various semi-conductor materials, which convert solar radiation into electricity [4] - on their rooftops or investing in other renewable energy devices. These smaller grid systems link localized power sources, often referred to as "distributed generation" sources. This scenario is challenging energy management systems because the supply of electricity on the grid has to equal demand to cope with the changes in renewables. However, more importantly, people can now choose to power their homes via a range of local renewable energy sources, and store or sell excess energy in their electric vehicles, home battery systems or to their neighbors. This is made possible by participating in a P2P energy trading network, which consists of a community of energy users composed of both consumers and prosumers - i.e. users equipped with small-scale energy generation units (like rooftop solar PV panels), which function as both energy producer and consumer [5]. Within a microgrid energy market, prosumers can store their energy surplus within a storage device, if there is any, or use it to supply peers in energy need [6]. Two are the main components enabling the energy exchange within such network [7]: (1) a virtual energy trading platform, i.e. the technical infrastructure which manages generation, demand and consumption data - collected through the smart meters installed within the house of each participant in the network - and performs payments; and (2) the physical energy network, i.e. a distribution grid where the energy exchange among peers takes place. To ensure accurate records of these transactions, microgrids are looking at blockchain technology. With the vanishing hype of cryptocurrencies distributed energy trading emerges as one of the most promising areas of application for blockchain technology. In fact, blockchain is one viable way to decentralize and share the microgrid accounting both in developed countries (facing the pressures of reducing their environmental impact), but also in developing countries (where segments of the population don't have access to national grids and centralized energy production).

The contribution of this paper is threefold. First, we position the challenges of blockchain technology for HCI research with a particular emphasis on issues of technology adoption and trust. Second, we illustrate through the design and real-world deployment of a neighborhood P2P energy trading system how these technologies challenge people's perceptions of energy and its trading and sharing. Third, we summarize our findings in terms of relevant design concepts such as economic rationality, rewarding, community, transparency and trust. We then conclude summarizing these findings as lessons learned on deployment of Distributed Ledger Technologies (DLT) for decentralized energy systems and design guidance for further HCI research in the domain of energy infrastructure and sustainable HCI in general.

2 Related Work

While much research addresses the technical shortcomings of DLT, not much investigation was conducted on the HCI front. Elsden et al. [8] argue that the field of HCI has evolved, spreading beyond the traditional domain of user interfaces into more profound questions surrounding the impact of new technologies on people. In their work, the authors outline the main groups of blockchain applications currently on the market by examining over 200 blockchain startups and their distinctive features. By doing so, they have set out a 'blueprint' for HCI researchers into the challenges and opportunities of blockchain technologies for the field.

Recent work by Sas and Khairuddin [9] focuses on the earliest blockchain application, Bitcoin, and explores the trust issues surrounding the use of bitcoins and cryptocurrencies alike. The authors argue that blockchain offers a unique case study for the exploration of trust since previous work undertaken in the field has focused on e-commerce and e-payment systems which are traditionally centralized, heavily regulated and non-anonymous. In addition, it must be pointed out that despite the extensive body of literature on trust in business-to-consumer (B2C) e-commerce [10–14], the role of trust in consumer-to-consumer (C2C) markets has received little attention, with few significant contributions to date [15–17]. Within this context, it is particularly worth mentioning the model proposed by Hawlitschek et al. [18]. In this work, the authors regard trust as a complex construct with multiple targets (peers, platform and product) and dimensions (ability, integrity, and benevolence), which are addressed from two different perspectives: the one of the buyer and the one of the supplier. Their findings highlight the pivotal role of the platform – which "primarily acts as a mediator between the peers" – in establishing trust among users, concluding that "trust towards the platform significantly increase users' sharing intentions–both for the supply and the demand side" [18]. This conceptual model provides an important contribution towards understanding trust in P2P markets, nevertheless, one can argue about its applicability to a blockchain-based system where there is no such trusted intermediary [19]. As blockchain technologies are decentralized, unregulated and anonymous, Sas and Khairuddin [9] claim that the applicability of previous HCI models on trust to the emerging domain of blockchain is questionable and new frameworks need to be established. The study builds upon a previous work by the same authors [20] on trust in bitcoin technology which aimed to establish one such framework for HCI research. In this early paper, the authors classify three different types of trust – technological, social and institutional. The users' trust in the technology can be divided into the perceived advantages of the technology, its usability and the perceived skills of the user to work with it. The social trust can be described as the level of trust between the different stakeholders engaged with the technology. Finally, the institutional trust applies to the rules and regulations surrounding each activity attributed to the technology.

The present paper explores all the above aspects regarding the technological, social and institutional trust behind new energy infrastructures based on P2P energy trading and combines them with a set of novel features unique to energy trading in distributed energy infrastructures. Parallel to the work by Sas and Khairuddin [9] who conducted 20 semi-structured interviews of bitcoin users in an attempt to identify trust characteristics not yet known to HCI researchers and the wider public, here we strive to detect further trust implications specific to P2P energy trading applications. Although blockchain applications vary in their purpose, the underlying technology is inherently identical. Therefore, it is pertinent to shed light on several challenges and opportunities discussed in the HCI community.

2.1 Challenges to Blockchain Technology Adoption

Arguably the most common challenge mentioned in the scientific community related to adoption of blockchain concerns the required level of trust among actors. Whereas in a centralized and regulated system trust is handed to either a third party or a government entity, in blockchain applications trust is diffused among the individual participants. Elsden et al. [8] state that blockchain facilitates transactions, consensus and shared history between otherwise 'trustless' actors. Trustless refers to the lack of a centralized body in blockchain applications. The concept of a 'trustless trust' states that certain activities are made trustworthy by not needing to trust anyone in particular. Elseden and colleagues base their work on the hypothesis that the trust among new actors is sealed by the trust in the robust technical protocols behind blockchain, thus eliminating the human factor. In such a model, paradoxically, the lack of human involvement in the governance of technology leads to a higher level of trust among the stakeholders. Sas and Khairuddin [9] argue that despite the robustness of the technology, one cannot simply eliminate or disregard the human factor. In their research ([9] and [20]), the authors emphasize the considerable risk brought by 'dishonest partners of transaction'. In the later study [9], they report on the distrust some users have towards the community, several of whom have been cheated, demonstrating the need to have more information about the users one is engaging with and more importantly, their integrity and moral code. The authors also underline the lack of verification procedures surrounding blockchain applications. They identify four different types of insecure transactions, the majority of which are related to human factors. Namely, the insecurity can arise due to users themselves, the other user engaged in the transaction, a person or an entity not engaged in the transaction and the inability of the technology to address all of the above.

The lack of information and understanding is a further aspect which needs to be investigated by the HCI community. Sas and Khairuddin [20] claim that merchants, i.e. sellers, feel challenged by their limited knowledge about the buyer and worry if they will receive their payment from them. The same can be said about the buyers who might not be confident in the quality of the service they will receive. The authors report that this mutual distrust arises from the limited information both sides have on how the technology works and on the identities of the actors involved. The lack of information and/or understanding of the technology is also mentioned by Elseden et al. [8], which further hint at the perplexity of tokenization and question whether a token can correctly represent the true value of a service. In addition, Sas and Khairuddin [9] brings the issue of reputation surrounding blockchain, which has often been linked with online black-market activities.

Finally, Sas and Khairuddin [9] shed light into a new aspect previously not studied – data privacy. The authors question whether users are aware of the consequences of sharing their data and preferences via smart contracts and whether the 'right to be forgotten' will have any standing in blockchain applications. This is a question of governance and rules and it has been classified as institutional trust. Though, how can users exercise institutional trust in blockchain technologies which are inherently built upon a *laissez faire* principle? All of those are important questions for the HCI community.

Besides the challenges described in the academic literature, which also apply to our energy infrastructure case study, after an extensive analysis of existing P2P energy trading platforms, we have identified automations as an additional aspect deserving further investigation. P2P energy trading applications are built out of the strive for more efficient and intelligent energy systems which give greater control to users. However, the lack of literacy on the subject matter and the possible enigma which such new technologies can represent to users can be a challenge. Even though some platforms offer their users the ability to trade manually and set different preferences for each trade, most existing businesses operate under the 'install and forget' principle. That is, after the initial installation and set-up of preferred parameters, users are no longer required to participate in the market actively. The system executes the trades automatically given the preferred time of day, amount of energy required and/or offered and more. Such automation is envisioned to reduce the perception of complexity users might have about blockchain technologies and improve the ease of use. Yet, one overarching research question we ask in this paper is to what extent does automation facilitate the increase in blockchain technology adoption for distributed energy infrastructures.

2.2 Adoption Drivers

The majority of HCI research done on DLT has focused predominantly on the challenges rather than the drivers behind their adoption. It is Sas and Khairuddin [9] who have paved the way by identifying several favorable aspects of blockchain which could strengthen users' motivation to adopt the technology. The decentralized nature of the technology is the first main driver. According to the semi-structured interviews conducted by the authors, users appreciate the lack of a third-party financial institution when executing transactions. Moreover, third parties have often been perceived as untrustworthy and rather deceitful. If a token is viewed in the same way as an asset, then in blockchain applications the user is the sole owner of that asset, an element strongly welcomed by interviewees. This is closely connected to the second major motivation Sas and Khairuddin have pinpointed - blockchain is unregulated. As a result of the perception of 'regaining control' over one's business, most participants in the study have claimed to feel more empowered and privileged. Blockchain represents not only a revolution in technology, but also a grassroots movement. Carrying a bitter-sweet anarchist sentiment, or rather 'militant' [9], this view is strongly connected to the negative notion of governments and central power who in users' perspective have become the enemies of the people. The lack of absolute power in blockchain applications means that the probability of abuse of this power over users' assets is highly minimized. In such a model, the decrease in risk contributes to the increase of trust. Users also acknowledge the simplified authorization process involved in making transactions in comparison to the overcomplicated central system. This in turn leads to faster, almost instant transactions. Finally, the ease of use has also been highlighted as a major contributor to the increase in trust. Besides the technology-related motivations, blockchain is also described as a tool to boost democracy [8]. It is claimed that blockchain applications encourage the establishment of flatter and more decentralized democratic organizations on the local level. Elseden et al. [8] call this the ability of blockchain to 'harness crowds and publics' in order to challenge central authority. Nonetheless, one can have a different interpretation of such a development and argue that whereas it is an opportunity for users, it represents a considerable challenge to governments. This is also valid for P2P energy trading applications which have the ability to create local communities and challenge large electricity retailers.

P2P energy trading is revolutionary not only in its use of blockchain systems, but also in the further boost of decentralized energy generation and sourcing of local power. Previous HCI research in those domains is highly limited, thus further investigation is needed. In their study, Meeuw et al. [21] examine the importance of locally sourced power for users in Switzerland. Through their work, the authors determine that the demand for renewable energy is equally high to the demand for locally sourced energy. They claim that in our traditional energy system, the services offered by utility companies lack transparency, do not offer any sort of control to their customers and no information on where their energy has been produced or consumed. P2P energy trading applications can change that. Meeuw et al. believe that if the consumers have a greater understanding of how the electrical system works and are given more customized information regarding their own production or consumption, wider technology adoption will be secured. However, the authors also claim that transactions on the blockchain can also be perceived as insecure which, in the authors' view, severely limits the acceptance of the technology. Furthermore, they report on the reluctance of rooftop-photovoltaic (PV) owners to share data, particularly the location of their systems. This is an important aspect which needs to be further investigated with participants in P2P energy trading activities.

3 PowerShare

To better understand people's perceptions of novel energy infrastructures we developed and deployed an energy monitoring and sharing system called *PowerShare*. The *PowerShare* application is connected with an Energy Trading Management System (ETMS) that is responsible for managing users' accounts, energy demand and offer, and providing data about the users' overall energy consumption and production acquired from smart-meters. The overall system was part of a larger pilot developed in the context of the H2020 SMILE (SMart IsLand Energy systems) project - www.h2020smile.eu.

3.1 System Architecture

PowerShare comprises a mobile application developed for Android devices (running Android 4.4.2 or higher with API level $\geq$ 19), through which users are given the opportunity to set criteria for energy trading (e.g. price per kWh), access their cryptocurrency wallet (in this case IOTA - www.iota.org), keep track of the transactions performed, and get feedback on their energy consumption and production patterns. For the purpose of our study, we provided participants with an initial IOTA balance corresponding to around 10 €. The application connects to an Energy Trading Management System (ETMS), which receives production and consumption data from the smart meters installed in each household and manages the energy exchanges thus simulating a future distributed P2P energy infrastructure. In addition, since none of the participants in the study has an energy storage system, production and consumption data collected through the smart meters were used to simulate a 3000 W battery (one for each household), which was "virtually" charged and discharged by the ETMS.

3.2 Mobile Application Design

The *PowerShare* mobile application was designed based on the analysis of existing platforms for P2P energy trading and the review of previous studies on energy feedback [22–27]. A first low-fi prototype of the app was subjected to heuristic evaluation, and then pilot tested with a small group of researchers and students from the Interactive Technologies Institute in Madeira. Based on results from the pilot test, we identified and removed the main bottlenecks concerning both the UI layout and the navigation flow. A revised low-fi prototype was then developed and tested with different subjects (similar to the previous sample in terms of demographic characteristics, but with no experience of the first prototype).

The app consists of six main sections and is structured as follows:

Home. The "home" provides real-time feedback (i.e. current production and consumption) and displays information about (a) amount of energy available for trading, (b) current day's transactions, and (c) share of renewable energy consumption on the user's overall weekly energy consumption. As shown in Fig. 1a, real-time feedback is always displayed on the screen, while the other information is accessible through a tab menu. This choice is due to the fact that real-time feedback has been found to be particularly effective in raising people awareness on their energy use patterns [22–24] and, since it provides an overview of the user's current production and consumption, can be extremely useful to quickly react to variations in the user energy demand - e.g. increase energy offer in case the battery is full and consumption unusually low.

Historical Feedback. As shown in Fig. 1b, this section provides an overview of consumption and production data over time, with three different levels of temporal granularity (daily, weekly and monthly). Historical feedback was found to be one of the most important features of an energy feedback system [25, 26] and, at the same time, provides a set of information that could support users in better understanding their energy behaviors and thus, identifying the best criteria for purchasing and/or selling energy surplus accordingly. For this reason, the information is presented in a great deal of detail, providing the breakdown of both production and consumption (e.g. consumption is divided in energy purchased from the traditional supplier, supplied by peers, and self-consumption).

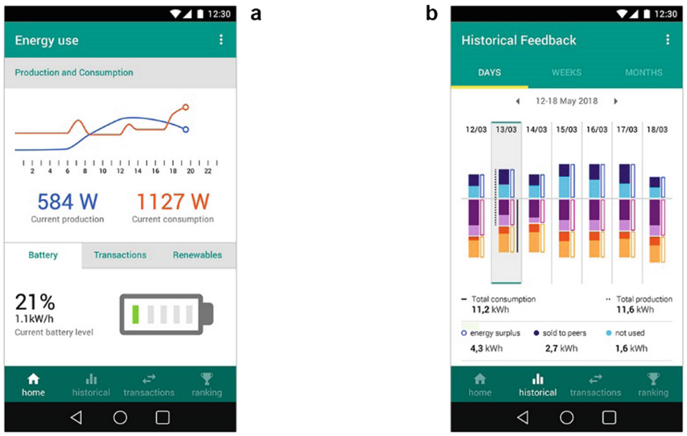

Fig. 1. "Home" (a) and "Historical feedback" (b).

Transactions. This section comprises the definition of criteria for purchasing and/or selling energy surplus - e.g. price per kWh - (see Fig. 2a), and a list of all transactions made by the user (see Fig. 2b). As shown in Fig. 2a, the price per kWh is the only mandatory field, with two options between which one is to choose: (1) a fixed price ("minimum" in case of selling and "maximum" in case of purchasing), or (2) a price tied to the one contracted with the electricity company. The latter option is specifically targeted to consumers that are subjected to dynamic pricing - i.e. the cost for energy purchased varies throughout the day based on market demands. Optional trading criteria are: (1) definition of specific time slots for trading; (2) limit trading to a list of selected buyers and/or suppliers; and (3) set a portion of the overall battery capacity to keep for self-consumption only. While registering the account, users are provided with the opportunity to choose between two trading modes - i.e. "automatic" and "manual". By selecting the automatic mode, users can start trading immediately, while if choosing manual mode, they have to access the "Transactions" section and set purchasing and selling criteria. A dialog window informs users about the possibility to modify this choice at any time through their profile settings.

Ranking. Since social comparison was proven to be effective in fostering sustainable behaviors [27], this section was designed to show the comparison between renewable energy consumption shares of all users (see Fig. 2c). Each week, the list of top ten most 'green' users is released. While registering the account, users are asked for permission to share this information with the community - i.e. user name and his/her renewable energy consumption share - and informed that they can modify this choice at any time by accessing their profile settings.

Wallet. The IOTA cryptocurrency wallet is accessible from an overflow menu. It provides users with the opportunity to check their mIOTA balance and manage payments.

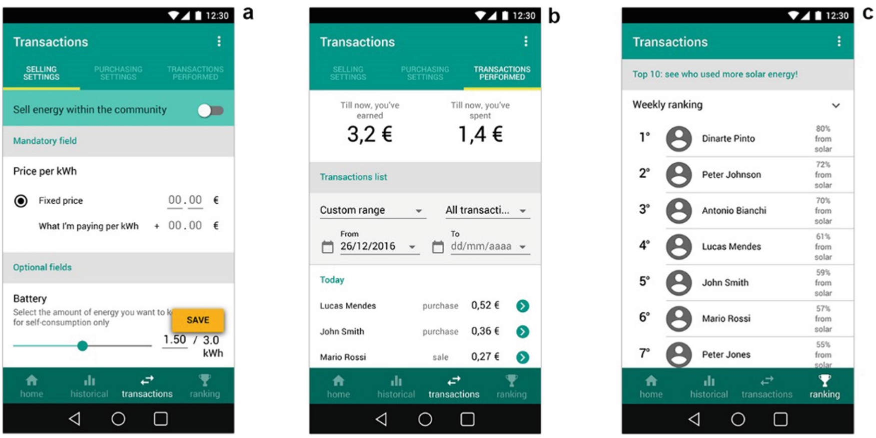

Fig. 2. "Transactions" (a–b) and "Ranking" (c).

Settings. This section, accessible from the overflow menu, simply serves to access and modify the account settings.

4 Methods

In order to investigate the human aspects affecting users' engagement with P2P energy trading systems, a small empirical study was designed and conducted in Funchal (Madeira Island). Ten residential prosumers living within the same neighborhood community were recruited through snowball sampling and asked to use *PowerShare* for a month. Nine out of the ten participants recruited took part in the study (one decided to withdraw). The households have from 1 to 6 family members, with an average of three people per household. Five families out of nine have children with ages ranging from 4 to 22 years. Age ranges of participants and family members vary between 4 years old and 81 (average age is 35.55 years old). Professional occupation and educational background are very diverse among the sample. All participants in the study are prosumers and own solar PV panels. At the beginning of the study, participants had an average of 6 months experience as energy prosumers. Informed consent was provided to all participants. The research team verified the existing communication infrastructure (internet connection) and, together with local technicians, installed the required equipment (smart meters and gateways) to collect production and consumption data. Baseline data was collected for a period of two months.

The system deployment started at the beginning of September and lasted four weeks. An Android tablet was provided to those participants that did not have a mobile device matching the minimum requirements for running the app. In addition, all participants received a weekly email providing a summary of their energy consumption, production and exchange. Interactions with the mobile application have been electronically monitored throughout the study.

4.1 Quantitative Data

At the end of the four-weeks deployment, a total of 333 transactions were performed (around 12 transactions on average per day), corresponding to about 7.5 kWh of energy shared among the community (see Table 1). Overall, we counted a total of 548 users' sessions. Concerning their distribution over time, no significant difference between weekdays and weekends was found. The average duration of user session was 135 s. Particularly noteworthy is the fact that, even though all participants in the study selected the "automatic settings" for both selling and purchasing energy, they did access "Transactions" and checked trading criteria.

Table 1. Summary of production, consumption, and energy exchanged (in kWh).

	Week 1	Week 2	Week 3	Week 4	Total
Production	31,04	107,15	131,4	150,9	**420,49**
Consumption	202,85	431,36	450,37	476,62	**1561,2**
Exchanged	0	1,39	3,33	2,64	**7,36**

4.2 Qualitative Data

At the end of the one-month deployment, semi-structured individual interviews were conducted with participants to explore their understanding, concerns, and motivations for engaging in P2P energy trading. Interviews started with a warm-up discussion about perceived advantages/disadvantages of engaging in P2P energy trading. Other questions targeted the way participants used the application (e.g. when and how often, most and less used features, usability issues faced, etc.), as well as their needs and motivations as users for engaging with the system. In addition, questions related to privacy, blockchain and cryptocurrency were included. Interviews took place in the respondents' home, lasted an average of 30 min, and were fully recorded and transcribed.

A general inductive approach was adopted for thematic data analysis [28]. All individual statements were printed on separate cards. Affinity diagrams were used to identify main themes and develop categories. To ensure reliability of the analysis, two researchers analyzed and coded each interview independently. Resulting themes and categories were compared and discussed. The researchers deliberated on coding discrepancies and disagreements, until consensus was reached.

5 Results

In this section we start by outlining users' motivation for engaging in P2P energy trading. We then describe the main characteristics of DLT and how they affect adoption of a P2P energy trading platform, and finally dive into the way people used the system.

5.1 Motivations to Engage in P2P Energy Trading

Economic Rationale. In line with previous work [29], we observed the emergence of the rational-economic model as of the main reasons for becoming a prosumer. This model assumes that people are willing to engage in behaviors that are economically advantageous: "*I have high consumption, compared to the average, because all my appliances are electric…we don't use gas. For this reason, I'd like to further increase my production capacity to cover my energy needs*" (Participant 4). However, our results suggest that economic factors are not the main motivation for engaging in energy trading. Despite the rational of several P2P energy trading platforms presented to prosumers as a way to further monetize their generation assets, results from our findings show that energy trading is not perceived as a business opportunity: "*I saw my transactions history on the app, but…it is very little, around 2 €…something really little.* (He opened the app) *See, I've spent 2,40 € and gained just 0,28 €. It is very little. I was expecting to get more. […] Personally, I'd like to install more panels and increase my production…but in my case it would be only for self-consumption purpose. Of course, if in ten years my consumption would decrease, leading me to have surplus energy, then, in that case, I'm fine with selling it!*" (Participant 2); "*I don't bother with earning money with the app. I was more interested in understanding how the system could work and how well solar panels work in this context.*" (Participant 5).

Sense of Community. While the economic rationale seems not to be a strong motivation for engaging in P2P energy trading, several participants mentioned the sense of community as an important aspect: "*I like the idea of trading with neighbors. That is true! We live close, we know each other, we are friends*" (Participant 3). Interestingly, one of the people interviewed said that he would be also willing to share his surplus energy with neighbors for free, further suggesting that the sense of being part of and act as a community is more valuable than any economic incentive: "*The electricity company is an anonymous entity, while my neighbors are people I know. […] Trading with neighbors, to me, is more like an excuse to start a conversation…to have a chat with them, like 'look, I've sold you energy today'. […] If I'm giving my surplus to a neighbor I don't care being paid for it, because there is a neighborhood's relationship between us*" (Participant 2).

Individual Intrinsic Reward. We found that engaging in P2P energy trading could also provide some kind of individual intrinsic reward in the form of personal gratification. On the one hand, the system is perceived as something that requires some expertise, which consequently identifies the user as an expert: "*Some people may have difficulties engaging with this kind of system. I'd be willing to use it but other people… it depends on your knowledge and background. It's not an easy thing; it is not for everyone*" (Participant 7). On the other hand, we noticed that engaging in P2P energy trading seems to have an effect on pro-environmental personal norm activation [29], by positively affecting people's moral and emotional beliefs: "[about P2P energy trading] *as a concept…I mean, we know it is renewable energy. It has a different impact. It makes me feel better, as a person, because I'm exploiting natural resources*" (Participant 2).

Transparent, Secure and Fair Billing. Interviewees also mentioned the opportunity to access real-time data, based on actual meter readings, as a valuable aspect of using this system: "*A big advantage of this system relates to metering and billing. The current billing system is based on consumption estimation. Actual meter readings are not carried out so frequently. With this system we have access to real-time data. It is automatic and based on actual data. This is important!*" (Participant 1).

5.2 Characteristics of Distributed Ledger Technologies and Their Impact on Users' Adoption of P2P Energy Trading Systems

As suggested in the related work, several of the main characteristics of DLT could turn into barriers towards their adoption. Building from our findings, in the following sections we describe some of those characteristics and their impact on users' intention to engage in P2P energy trading.

Trust in a Trustless System. DLT, like blockchain technology, are often defined as "trustless" [9]. Indeed, due to their decentralized consensus mechanism, they do not require a third-party trusted central authority to validate transactions. Decentralization is one of the cornerstones of DLT, which allows for fast transactions at low costs. Nevertheless, several researchers seem to agree that this may also raise serious trust issues among users [8, 20, 30]. Among our interviewees, only one mentioned some concerns about the lack of a central authority (institutional trust): "*I'd prefer having a central entity managing the system. Some kind of institution I can trust*" (Participant 9). It should be also pointed out that Participant 9 is new in the neighborhood and still doesn't know many people there. We believe this aspect may have a big impact on trust, since all other interviewees, when asked about possible trust issues, did not express any concern about this aspect, stressing the fact that they are members of the same community and know each other (trust between users): "*They are my neighbors. I know them. I trust them*" (Participant 3). In addition, our findings suggest that transparency of the system (trust in the technology), which is another core feature of DLS, would further mitigate concerns due to the lack of a trusted central entity: "*I think the system is trustworthy. I'd feel comfortable using it because…I mean, I can go check all transactions I've performed*" (Participant 1); "*I don't see any security issue…I'd feel comfortable using it. The platform is clear. I can see the amount of energy I consumed, energy I could have consumed from neighbors or sold to them. I think, yes. It is transparent from this perspective*" (Participant 4).

Data Sharing and Privacy Concerns. Another aspect representing a potential barrier in using DLT is the pseudo-anonymity of traders [9]. To work around this issue in *PowerShare* users are de-anonymized, so that every trader can see the list of all community members and with whom he/she has traded. In addition, in order to test the effectiveness of social comparison in keeping users engaged with the application, (with permission from the user) the share of RES in his/her overall energy consumption is displayed in the weekly ranking. We believed that this workaround could strongly increase transparency and trust in the system but, contemporarily, may also raise some privacy issues. Surprisingly, only one respondent reported little concern with sharing the above-mentioned information: "*I don't think this kind of data could be of any* *harm…energy usage is not like personal health information…in a way, it's kind of neutral. […] But, probably, I'd prefer to not share that information with the others since I'm living by myself and I'm a woman*" (Participant 9). Two other participants mentioned a possible risk linked to the information provided through the weekly ranking, even though they both specified it is not a concern for them: "*There might be people who don't want to share their percentage of renewable energy consumption, since a change in their weekly consumption may reveal that they are not at home. This is the only issue I can think about, but it is not a concern to me*" (Participant 7); "*Perhaps, knowing people consumption details could be used for commercial purposes or could disclose personal information, like when you're at home or not…but…no, I am not overly concerned with privacy of my energy data*" (Participant 6). All the other participants clearly stated that sharing such information was not an issue.

Technology's Embedded Complexity. Results from our study show that DLT are perceived as extremely technical and not easy to understand for non-specialists. In line with what was hypothesized by [8], this aspect appeared to be a possible barrier towards the adoption of the system: "*it's extremely technical. There are a lot of codes… it's very engineeristic. I mean, if you are a geek it's ok, otherwise…no, it's too much*" (Participant 9). In general terms, we observe a lack of literacy on DLT and, especially, on cryptocurrencies, which leads people to be suspicious about them: "*I don't trust these things. I prefer to keep my feet rooted on the ground. To me they do not exist! I don't understand how cryptocurrencies work…who issues them?*" (Participant 7). Even though almost half of the interviewees claimed to be open to use cryptocurrencies as a medium of exchange for energy, several concerns have been raised: "*I don't know cryptocurrencies very well, but I'm open to them. The only cryptocurrency I use is PayPal, which, I think, is a kind of crypto…even if it is a prepaid account, since first I have to transfer money to my PayPal balance…it is a kind of crypto, isn't it?!…but it is not bitcoin. […] cryptocurrencies are less stable than fiat currencies. Also, they are not enough regulated and there is a lot of market speculation…especially with bitcoins. So, I guess there are some risks associated with cryptocurrencies. […] As a concept it seems fine to me, but it could be risky since the market is not very regulated*" (Participant 2), and "*I'd prefer to use fiat currencies. Mainly for security reason, in the sense that you always lose money when exchanging cryptocurrencies to fiat currencies…it is not worth it*" (Participant 3). Finally, in accordance with Elsden et al. [8], respondents questioned whether cryptocurrencies can represent the actual value of energy: "*I think that euros are more meaningful. A currency that is used in everyday life helps people understanding the value of what they are consuming, or trading, or sharing*" (Participant 9).

5.3 Usage Patterns and Information Needs

Effectiveness of Social-Comparison. In line with previous work [31, 32], our findings suggest that social-comparison is an effective strategy to keep users engaged with the system and influence energy-related behavior in households. The weekly ranking provided by *PowerShare* was indeed one of the most popular features among participants in the study: "*I used to check the ranking. […] some days I was in the top positions. It is cool.* [the ranking] *is an interesting idea*" (Participant 3). Competing with other users appeared to be a silent motivation for improving participants' individual performance, pushing them to increase the share of RES in their overall energy consumption, and thus leading users to be more willing to engage in P2P energy trading: "*I must confess! The feature I used the most was the Ranking. You know, to see how I was doing in terms of green energy consumption. […] My main concern relates to using more green energy…so, I'd be willing to improve my installation and engage in energy trading*" (Participant 1).

Social Inaccessibility. We noticed that it was almost always the householder the only one taking over the task of using the system: "*I was the only one using the app. My wife doesn't care about it* (laugh)*…she doesn't care if she is consuming a lot of energy. My kids…I've tried to show them the app but, it didn't catch their attention…they don't care…they don't pay the bill* (laugh)" (Participant 2). Lack of interest for energy-related behavior in those family members that are not responsible for managing households' expenses has been widely observed in previous studies [31]. Despite several studies on user engagement with eco-feedback applications have been conducted to explore different strategies for designing more engaging systems [29, 33–35], a lot of work still needs to be done in this area, which represents an interesting challenge for HCI research.

Learning-Before-Doing. An interesting aspect that emerged from the interviews was that some users started exploring the transactions settings later on during the study. In fact, after going through a learning period to better understand their energy usage patterns, they reported: "*I've set parameters two days ago* (he explained parameters selected). *It took me a while to fully explore the app. At the very beginning I used the app only from my perspective: how much energy I am producing or consuming…this, to manage my consumption differently. For example, taking advantage of high production to use the washing machine. Then, I've explored it a bit more and defined some trading criteria*" (Participant 2). During the interviews, users have also asked questions and suggested further improvements to the application in terms of information provided, thus demonstrating interest and willingness to become more proficient with the system: "*I have a doubt…here, in the historical feedback. Now, there is no battery, it's simulated. Ok?! So, is the 'self-consumption from battery' included in my 'overall consumption'? […] Are batteries expensive? What could it be the price for a, let's say, 3 kWh battery? […] I'd like to have more control over my consumption. Like knowing the actual consumption of different appliances and which one consumes the most*" (Participant 7); and "*Can I still modify the settings? Can I play with it? Transactions aren't real, I know, but…it's just to get an idea of the potential of such system*" (Participant 4).

In addition, the quantitative usage patterns collected support this conclusion. Several participants reported to use the application daily (even more than once per day), to check their performance: "*I used it almost every day. Especially at the end of the day, to check my overall daily consumption, and around midday to get an idea of peak production*" (Participant 7), as well as to make far-reaching inferences about their consumption and production patterns, and adapt their behaviors based on the feedback received: "*I use the app to check and control our production…to understand which are the hours of peak production, and take advantage of them […]. I look at it mainly at the end of the day, or whenever I am at home, to make comparisons and control consumption as well. For example, when the production is high, I turn on the dishwasher*" (Participant 8).

Different Ways for Providing Feedback Data. An interesting aspect that emerged from the interviews was that people seem to prefer accessing eco-feedback data through different channels. When asked about the weekly summary received via email, almost all interviewees reported to consider it as useful as the information provided through the app: "*I'm satisfied with the information provided through the application, but also the weekly summary was useful. I think they complement each other. I mean, on the app I can see my daily performance, while, through the summary, I can also get an idea of how my performance is evolving*" (Participant 1). In addition, we noticed that the weekly summary has been found particularly useful to keep track of participants' performance when their interaction with the system was affected by lack of time: "*I used to check both the app and the weekly summary, depending on my schedule. When I was particularly busy, I only looked at the summary, but when I had more free time, and especially at the beginning of the study, I mostly used the app*" (Participant 4). Several users also mentioned the possibility of accessing feedback data through a web-page as a valuable improvement to the system: "*I'd prefer to access the system on the web. Like, through a website or a web-page where I can see my data. I think it would have been great to have that opportunity*" (Participant 4).

One last aspect that should be taken into account, is the way data are presented. All interviewees appreciated having data about production, consumption and energy exchanges represented in a visual form. One of them, clearly explained his preference for this form of presentation by comparing the app with the monthly bill: "*The bill is not easy to read. I guess it provides a lot of information, but it is confusing. It has a lot of numbers and text…and everything is too small*" (Participant 1).

6 Discussion

Based on our findings deploying DLT for energy systems, we elaborate guidelines to inform the design of P2P energy trading platforms. These findings sustain the need for further HCI research in the domain of energy infrastructure and sustainable HCI in general since they ultimately depend on end-user adoption. In order for these new infrastructures to evolve they need to move beyond addressing economic rationality to address issues of trust, control, transparency, learning and the family/community context.

6.1 Supporting Transparency and Control

As reported by [8, 9], limited understanding of DLT could strongly impact users trust in the technology. Transparency of the system is fundamental to mitigate this potential barrier; thus, a P2P platform should provide easy access to accurate and detailed real-time production, consumption and transaction data. For the same reason, users need to feel they have control over the system. Despite all participants in our study selected the automatic mode, several of them reported to feel reassured by having the opportunity to manually define criteria for trading. This suggests that full-automation - i.e. the 'install and forget' principle -, which is part of the value proposition of several existing P2P energy trading platforms, may not be as effective as expected. Another design implication, related to transparency and control, deals with data sharing. Although none of the interviewees reported concerns about sharing data within the community, they seem to be aware of the possible consequences this could bring. Therefore, a P2P energy trading platform should always provide users with high control over their data and personal information.

6.2 Designing Around People, Not the Technology

Findings indicate that DLT are perceived as extremely technical and not easy to understand for non-specialists. While designing a P2P energy trading platform a major effort should be devoted to 'translating' the technology behind the system. Cryptocurrencies should be presented as an asset, while all monetary values reported in conventional currencies (€ or $). Processes should be simplified, data entry made as easy as possible, and all confusing, abstract or useless information should be removed (e.g. 'wallet password' instead of 'IOTA seed password'). For the same reason, data should preferably be provided in a visual form.

6.3 Supporting Learning

Before actively engaging in energy trading, people need to go through a learning period to get a better understanding of their energy usage patterns. Providing detailed information (e.g. both real-time and historical feedback, multiple levels of temporal granularity, production and consumption breakdown) is an effective strategy for fostering the adoption of such system. Contemporarily, in order to avoid information overload, as well as to meet different routines and schedules, the information should be spread across multiple channels. A mobile application, for example, may serves the purpose of providing glanceable information - e.g. real-time feedback - users can quickly act (and react) upon. While a website would be more suitable for providing data with a great deal of detail, allowing users to make comparisons, inferences, and finally come to understand their habits.

6.4 Leveraging Sense of Community to Mitigate Lack of Institutional Trust

Findings suggest that developing a P2P energy trading community at neighborhood scale, where people are close and know each other, may be an effective strategy to mitigate the lack of institutional trust. In fact, in order to reduce the impact of not having a third-party central authority, we need to increase trust in peers. Nevertheless, things change when envisioning a wider application, for instance at the city level. Scaling up the system means creating a community where people might not know each other, which in turns is likely to negatively impact both trust and privacy concerns. In such scenario, fostering the sense of 'being part of a community' is even more crucial. A P2P energy trading community, especially a large-scale one, should be a 'space' where people sharing the same values are encouraged to act towards a common goal. Priority should be given to the result of a collective effort instead of individual achievements. Some interesting works in the field of social psychology [36–38] suggest indeed that collective efficacy – "the belief that groups of people are efficacious in solving tasks" [38] - is a strong driver for engaging in community pro-environmental behaviors. This leads us to hypothesize that a group contingency approach [39] could be an effective strategy for designing large-scale distributed energy infrastructures. Nonetheless, it has also been argued that trust remains a potential barrier towards cooperation [40]. Thus, the value of collective efficacy as a workaround for the scalability issue of P2P energy trading is still mere speculation and requires investigation.

6.5 Involving All Family Members

A further design implication that emerged from our study concerns the need of designing a system able to engage all family members. Based on our findings, we have identified two possible strategies to reach this goal. On the one hand, we can leverage social-comparison and motivational strategies, like rewards and competition, which could be particularly effective in engaging pre-teenage children. On the other hand, a design based on the norm-activation model, which shows the environmental impact of our behaviors and fosters a critical reflection on them, may induce feelings of accountability on those family members that are more concerned about issues related to parenting and family well-being.

7 Conclusion

In the last years efforts to decarbonize the electric grid have led to important changes in the energy infrastructure. For instance, the lower manufacturing costs of PV systems provides a cost-effective alternative to conventional power plants enabling end-users to reduce their energy bills and carbon footprints. In a scenario where a considerable portion of the energy is provided by local renewable sources the management of spinning resources is much more complex and unpredictable. There is a lot of buzz and deception around DLT at the moment, but their use in the energy sector could provide an ideal solution to a genuine problem. That is, the shared nature of energy resources and the difficulty of tracking the large volume of transactions – from energy supply and demand, to actual exchanges at the edge of the grid.

Despite several pilot projects currently running all over the world and much work being done to address the technical and regulatory aspects related to the application of DLT in the energy sector, our understanding of the human aspects affecting the adoption of P2P energy trading is still minimal. This paper attempts to fill this gap. Through the real-world deployment of *PowerShare*, a neighborhood P2P energy trading system, we explored how DLT challenge people's perceptions of energy and identified some relevant design implications for the development of these systems.

Besides the concepts described in HCI literature (i.e. trust, control and transparency), study findings have identified further drivers and challenges to DLT adoption not mentioned in previous studies (namely, learning and social context), which represent interesting directions for further HCI research. In particular, we argue the need of exploring the effectiveness of different design strategies - namely social pressure, norm activation, and group contingency - in improving users' engagement and accessibility of the system to all family members. Another aspect that deserve to be further investigated regards the way energy and its new infrastructure is represented. To increase transparency, and consequently support learning, the complex dynamics behind energy consumption, production and exchange should become clearly visible. How to do so, is a matter of further investigation. Most importantly, we encourage the HCI community to address the lack of understanding about P2P energy trading and DLT. Findings from the real-world deployment of *PowerShare* indicate that people are interested, open and willing to engage with such system. However, the embedded complexity of DLT, could make this a daunting challenge and thus become a barrier towards the successful implementation of distributed energy infrastructures. This is not a trivial issue, since it requires a deep understanding of how technologies shape and are shaped by social and cultural factors. The development of decentralized energy systems entails a paradigm shift which goes beyond technological change, thus implying the need of designing DLT applications around and together with users. It is precisely in this regard that HCI research could provide a major contribution, informing the development of a new and more sustainable energy system.

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