QUARTIERSTROM: A DECENTRALIZED LOCAL P2P ENERGY MARKET PILOT ON A SELF-GOVERNED BLOCKCHAIN

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ABSTRACT

Quartierstrom creates a local peer-to-peer marketplace for locally generated solar power. The marketplace is implemented on a permissioned blockchain governed by all prosumers. The utility participates in the market as the collector of grid usage tariffs and as a fallback-prosumer for any mismatch between market and physical flow of power. A dynamic grid usage tariff is implemented to align pure energy market incentives with grid stability interests. Privacy-by-design concepts are presented which guarantee that the user's individual load profile is not leaked to any third party albeit using a blockchain.

INTRODUCTION

More and more production of renewable electrical energy happens locally, in a decentralized fashion. It is politically desired to raise the ratio of renewable energy but many countries fade out their subsidies. Self-consumption is incentivized in many legislations in order to improve the profitability of renewables but is often restricted to buildings behind the same distribution grid connection.

Prosumers in Switzerland currently have no possibility to influence the level of remuneration for the local solar energy they sell or to sell their solar energy directly to local consumers. The Quartierstrom project investigates a transactional energy system that manages the exchange and remuneration of electricity between consumers, prosumers and the local grid provider in the absence of intermediaries.

The pilot grid in Walenstadt is operated by *Wasser- und Elektrizitätswerke Walenstadt* (WEW) in the Canton of Saint-Gall. 27 participants are prosumers with PV plants, 7 of which own battery storage systems. 10 participants are pure consumers. The local utility operates a grid-attached battery storage system and the nearby EV fast-charging station can participate in the market.

We designed a dynamic tariff for grid usage depending on A) the used/transversed grid levels (N1, N3, N5, N7) of decentrally produced and consumed units of energy and B) the voltages on N7 where the consumer is located. Such a tariff structure incentivizes local balancing, i.e. locally produced energy should be consumed concurrently and as close as possible to its source whenever possible.

The blockchain [1] is a novel technology suitable to implement local peer-to-peer markets. Both prosumers and consumers can indicate a price at which they are willing to sell / buy locally produced solar energy without the intermediation of a utility or any other trusted third party. Even if utilities still enjoy a lot of trust from their customers, this trust mainly lies in the utilities *integrity*, not in their *information security competence* nor in their *absence of curiousness* regarding personal data. If implemented correctly, blockchain solutions have the potential to guarantee transparency and integrity of the process, confidentiality and information security. In addition, system resilience is improved, as there is no single point of failure. On the other hand, blockchain technology is a natural choice to emphasize the bottom-up community spirit, attractive to many customers engaging in decentralized energy production.

The key goals of this project are A) the assessment of the technical feasibility of a blockchain-based community energy system regarding local utilization of solar energy, grid quality and energy efficiency and B) resulting dynamics regarding local market prices and user acceptance.

The Quartierstrom project is in field operation since December 2018 and customers are able to trade their energy using a web interface since January 2019. The field operation will run until the end of 2019.

BLOCKCHAIN PLATFORM

With the goal of a local peer-to-peer energy market in mind, we built a system that is distributed and secured by the participants and beneficiaries of it. We have chosen a blockchain-based approach to allow for mutual validation of the correctness of transactions, computation, and settlement of the system. The market application needs to be able to receive bid data from the participating nodes and execute functions, like matching and settling, in a fixed interval. The functionality can be split up into three distinct parts of the system, which are part of every participant of the system:

- *Data Acquisition*: Smart metering and read-out application

- *Data Management*: Agent and client application to process acquired data, issue transactions and manage signatures
- *Data Processing*: Full / light node for execution and validation of platform applications and subscription to updates

Even though *Data Acquisition* is separate from a blockchain-based functionality, it is part of the chain-of-trust, as measurement data is the basis for settlements in the market application. In addition, the smart meter is intended to host the computation of *Data Management* and *Processing* functionalities of the platform. As Figure 1 shows, every participant runs either a full or a light node to connect to the underlying blockchain, as well as the smart meter and agent modules [2].

The platform and its software modules are run on a SmartPi 2.0 device, which comprises a single board computer in the form of a Raspberry Pi 3, an expansion module to measure voltage and current, as well as a power supply. The device comes with a metering software that provides a REST interface to access instantaneous consumption and production measurements, as well as time series data of measured values.

Data Management

The management of actions, like sending out buy or sell orders or updating price preferences based on the acquired data, is handled on each of the end-user's devices. The Agent module performs the coordination of actions on the end-user's side of the system. While keeping in sync with the blockchain and its regularly published blocks, this module keeps information about the user's preferences, such as sell and buy prices, and follows the strategy according to its collected information. The strategy contains descriptions regarding the agent's objectives and issues buy or sell orders based on the current consumption and production. The client module contains the schemes for data types as well as methods for composing and signing transactions.

Data Processing

The issuance and signature authority within the platform's BFT based proof-of-stake consensus mechanism is distributed to the utility company and prosumer participants. Because of its natural monopoly on grid infrastructure, the utility takes care of registering participants for their respective marketplace and assigns authority to prosumers with a genuine PV for block validation. This design leads to a permissioned blockchain with an energy-efficient consensus algorithm, unlike bitcoin's proof-of-work [1], which purposely causes excessive energy consumption for block mining.

The platform utilizes the Tendermint consensus protocol, which allows for high adaptability due to its Application Blockchain Interface (ABCI) universally available to any programming language. Tendermint allows replicated state machines to be kept between arbitrary numbers of validators [3]. In addition, Tendermint offers a high amount of flexibility and customizability in order to adjust to particular application requirements such as the reduction of communication, creation of empty blocks, and time delay between blocks. The initial decision to trust prosumers in the systems is deducted under the assumption that these participants have already made an investment in the system (in the form of a PV plant). While the current distribution of voting power is equal for every active validating node, future enhancements of the platform may include an active staking mechanism to incorporate solar investment size while maintaining a valid equilibrium between the nodes.

DECENTRALIZED DOUBLE AUCTION

In order to create a successful peer-to-peer exchange for electricity in line with the overall objective of promoting sustainability, there should be incentives for local consumption of locally generated electricity, so the prices should reflect the instantaneous availability of local electricity. Although there are multiple articles promoting the technical feasibility of peer-to-peer electricity exchange using blockchain technology [4]–[7], only few provide details on how a successful market design for the

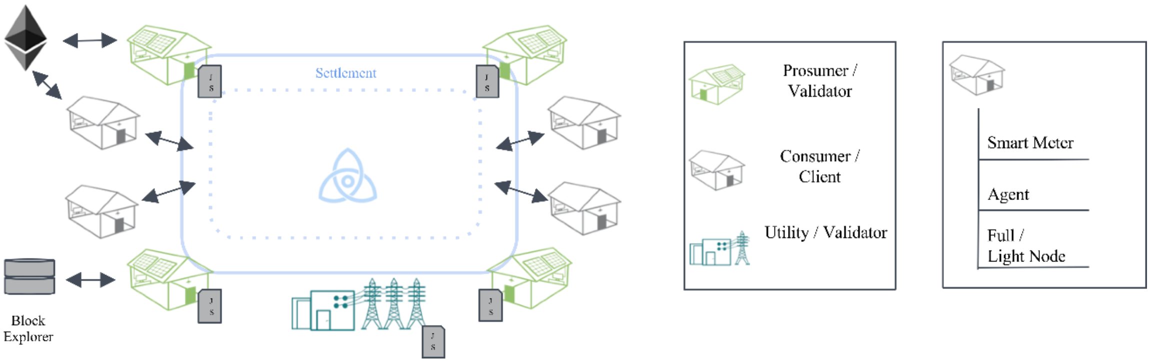

Figure 1 System Overview This figure shows the three main participant types of the system. The three modules for data acquisition (smart meter), data management (agent), and data processing (full/light) node, are part of every participant [2].

exchange should look like [8]. Yet, for a critically important good such as electricity, the allocation and pricing rules are the crucial factor defining whether a market runs successfully [9]. Decentralized exchanges represent complex multi-agent systems with volatile supply and demand and market participants show individual preferences and trading strategies [10].

Most existing wholesale electricity markets are governed by auction mechanisms. That means that participants express their preferences in bids, which contain a price and a commodity or quantity of commodities they wish to buy. All bids are collected in an order book and at distinct times, these orders are matched to form trades between the participants according to specific auction rules [11], [12].

It is a novel situation, that the households, which are currently merely price-takers in a retail market, change their roles to active prosumers and consumers, which influence electricity sourcing themselves.

A key task in the Quartierstrom market design was to create an auction in which all participants have the possibility to influence the prices for which they buy or sell electricity. While we do not necessarily expect all participants to adapt their prices frequently in the long run, we do believe this is a unique chance to elicit price preferences for local, renewable energy from individuals in a real setting. To the best of our knowledge, this is the first study, which allows individuals to actually influence the true prices they will pay.

There are numerous research studies on auction mechanisms and their implications for economic efficiency and price development. For instance, Klemperer argues that discriminatory price auctions foster a more competitive environment and that uniform price auctions are more prone to collusive behavior on one side of the market [13]. While a discriminatory price regime yields slightly higher average prices according to several different studies based on simulations and lab experiments [11], [14], discriminatory-price auctions can reduce volatility of prices as Rassenti et al. find in a lab experiment with students interacting in a simulation of the Californian electricity market [14].

Based on these findings, we have further identified a double auction with discriminative pricing as a suitable market mechanism for the Quartierstrom market. For both, consumers and prosumers, the smart meters transmit bids containing the price limit determined by the individual household and the electricity demand or supply measured by the meter. An order book collects all bids during discrete intervals of 15 minutes and orders them by price: Sell bids with a lower sell price are prioritized, and buy bids with a higher price respectively. Discriminative pricing in this setting means that for each trade, the price is derived as the mean between the respective buyer's and seller's price.

In the spirit of decentralization, the auction is implemented as a smart contract on the blockchain, which to the authors' knowledge is another novelty among peer-to-peer energy market projects.

PRIVACY BY DESIGN

The power consumption of each individual household is recorded every 15 minutes and placed on the market as a bid by means of a blockchain transaction. Linking bids for a particular participant reveals his usage profile, which is to be considered personal data. A simple blockchain only guarantees *pseudo anonymity* by representing each demand and production smart meter as a public key (the public key can be thought of as an account number in the traditional banking sense). No association between the public key and the household's address or occupant's identity is published on the blockchain at any point in time. However, third parties may be able to gain insights about consumer behavior, household characteristics or occupancy patterns from market orders. Because of their linkability risk, the European Blockchain Observatory considers public keys personal data under GDPR [15]. Quartierstrom therefore aims at breaking the linkability among subsequent market orders. The decentralized marketplace features a public order book, so price and amount of all orders are public. This transparency is desired so every observer can verify the market's integrity. However, the identity of a bid's originator does not need to be public as long as the market can enforce settlement of successfully cleared bids. Thanks to the blockchain, a cryptocurrency could be used to supply the necessary funds along with a bid using an atomic transaction. Such a cryptocurrency would have to feature private transactions to avoid linkability of bids.

As the group of users on a market is bound by the physical dimensions of the respective grid, *k*-anonymity [16] can be achieved at best, *k* being the number of participants per grid region.

The following approaches were evaluated as candidates for enhancements of the Quartierstrom system:

Zero Knowledge Proofs

The Zerocash protocol [17] as implemented by the Zcash cryptocurrency can deliver private transactions leveraging *zero knowledge succinct non-interactive arguments of knowledge* (zk-SNARKS) for coin mixing. Such proofs are still computationally heavy and are therefore not well suited for embedded devices. Moreover, clients must scan the blockchain for transactions involving themselves. Outsourcing this scanning would leak personal information.

Linkable Ring Signatures

The Cryptonote protocol [18] as implemented by the Monero cryptocurrency leverages linkable ring signatures for coin mixing. This approach does not demand much computational power but is not well suited for light nodes, as every participant has to scan the blockchain for transactions like in the case of Zerocash.

Trusted Execution Environments

Trusted execution environments (TEEs) allow running

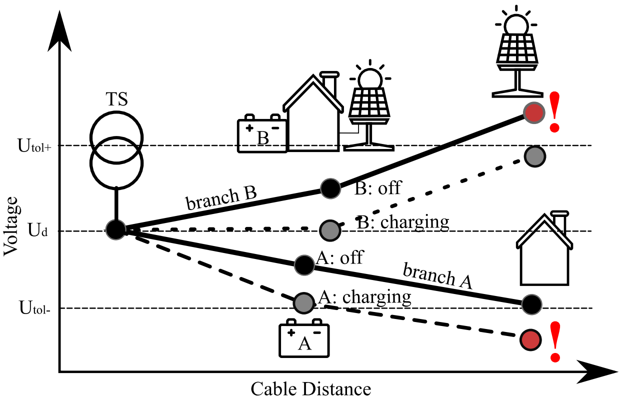

Figure 2 Voltage drop diagram. In order to support voltage stability, battery B is able to mitigate an overvoltage on branch B by charging (dotted line) whereas battery A, bidding on the same market, would cause an undervoltage on branch A by charging (dashed line)

code confidentially inside an enclave that is secured by hardware. Subject to trust in the manufacturer of the hardware, such TEEs can convince third parties of the integrity and confidentiality of a computation by remote attestation. [19], [20] and [21] proposed protocols for private transactions based on Intel SGX [22]. For embedded devices, ARM trustzone [23] could be leveraged.

DYNAMIC GRID USAGE TARIFF

If several power plants feed into the distribution grid at the same time with little consumption, the grid can get congested and undesirable overvoltages can occur. On the other hand, many electric vehicles that charge with high power during the same time of day can cause congestion and undervoltages. As shown in [24] and [25], voltage deviations can be mitigated by shifting flexible load and generation in time. Electric boilers and other flexible loads can draw power when the sun shines. Grid-attached batteries can soften both consumption and production peaks. However, one may not assume that improving the power balance in a community automatically improves voltage stability in any case, as shown in Figure 2. A battery system *A* installed on branch *A* may choose to charge because there is a lot of cheap PV energy produced on branch *B*, potentially causing an undervoltage on branch *B* while not improving the overvoltage on branch *A* by much. A pure energy market neglecting grid topology would risk to put additional strain on the grid.

Quartierstrom factors voltage stability into the market prices by using dynamic grid tariffs to incentivize grid-stabilizing behavior and improve profitability of well-placed storage systems. Our tariff design will reward battery *B* for charging while it would put a penalty on battery *A* for doing so. The integration of such tariff system is unique and to the authors knowledge not yet implemented in other pilot projects.

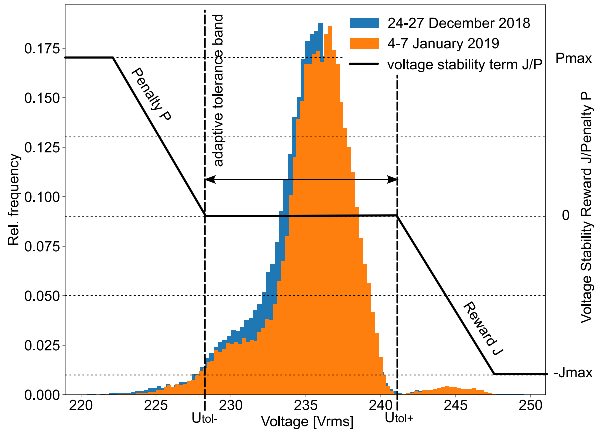

Figure 3 Voltage-dependent reward and penalty. The histogram shows voltages during two winter months. Based on instantaneous voltage deviation beyond an adaptive tolerance band, rewards are subtracted or penalties are added to the grid usage tariff charged for consumers.

Today's static grid tariff is equal for energy produced on all grid levels N1-N7: K_{1-7}=11 Rp./kWh. We replace it by K_7=6 Rp./kWh for trades within the same N7 grid within the community, downstream a shared substation. This shall reflect the infrastructure cost for N7 only. Moreover, a voltage-dependent reward/penalty term as shown in Figure 3 is added to the static tariffs. During uncritical operation when the grid voltage remains within a tolerance band, neither reward nor penalty apply. In case of heavy irradiation combined with low consumption, the voltage may rise beyond the tolerance band and the grid tariff (paid only by consumers) gets lowered to incentivize flexible loads to draw power. Allowing the tariff to become negative by using high rewards supports the business case of storage systems as they can earn not only by discharging but by charging as well, if and only if thereby offering a desired service to the grid. In the case of many coinciding loads like charging EV's, the voltage can drop below the tolerance band and the grid tariff raises in order to incentivize load shifting to other times.

While there are absolute voltage limits that need to be guaranteed by the utility, we want the market to react before these limits are reached. We therefore define an adaptive tolerance band based on the voltage histogram. This tolerance band can adapt to seasonal changes as well as to changed behavior or infrastructure in the respective grid.

Regulatory Challenges

Charging voltage-dependent grid usage tariffs can lead towards locational marginal pricing. Households further away from a transformer station would observe more volatile tariffs than those closer to it. This is politically undesired in Switzerland because it conflicts with the solidarity principle. From a market perspective, rewards and penalties must be significant in order to incentivize investments in infrastructure that allows to react to dynamic pricing.

The Quartierstrom project investigates a novel approach using path dependent grid tariffs that incentivize local balancing and grid friendly operation through voltage pricing. However, the optimal design of tariffs that allow utilities to recover grid costs and prosumers to amortize their investment costs likewise remains an open challenge and is beyond the scope of this article.

CONCLUSIONS

Quartierstrom is the first operative decentralized peer-to-peer marketplace for solar energy for communities covering entire low-voltage distribution grids where participants can choose their electricity price in a double auction. It is also the first such project to employ dynamic grid usage tariffs to factor in voltage stability. Further contributions include the design of a smart contract based auction process featuring privacy-by-design for all participants.

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