ETHome: Open-source blockchain based energy community controller

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ABSTRACT

This paper describes the proof of concept of a blockchain based organization of a local low voltage energy community. The focus of the concept is efficient use of shared resources to minimize external dependence, and not energy trading. A previously proposed control algorithm, which exploits the power dependency of the efficiency of electrical energy storages, is implemented as a smart contract on a private instance of an Ethereum blockchain to coordinate the operation. It is implemented using four connected Raspberry Pis representing the participating households with pre-given electrical load and photovoltaic conversion as well as a battery. Each household runs an Ethereum full node and an interfacing software. Only the energy technology components are simulated, while the blockchain is actually running on the Raspberry Pis in order to mind the full complexity of the technology. The practicability is proved in a test run and positive effects on the efficiency and the self-sufficiency within the community are observed. A first cost-benefit estimate is given and a further research agenda is presented.

CCS CONCEPTS

• **Hardware** → **Smart grid**; *Batteries*; *Renewable energy*; • **Networks** → **Peer-to-peer networks**; *Cyber-physical networks*; *End nodes*;

KEYWORDS

blockchain, open-source, energy community, battery efficiency

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1 INTRODUCTION

The landscape in the German electrical power system (EPS) is changing rapidly. The energy transition is political consensus [12]. With an increasing share of renewable energies [11, 41] the EPS becomes more and more decentralized and the number of actors in the EPS increases with high rates. In future, the EPS is going to become too

complex in order to be fully controlled via the traditional top-down approach. Thus new bottom-up concepts have to be investigated [2] and there is a need for new flexibility options [39].

Residential demand can be satisfied in a sustainable way by a combination of distributed photovoltaic (PV) and battery based energy storage system (ESS) [26]. If operated in a coordinated way, the ESSs of households in local energy communities have a large potential for an increase in efficiency and self-sufficiency [30].

A basic principle of automation engineering is that the optimal structure of the control technology represents the structure of the controlled process [2]. This motivates us to investigate controlling such an energy community in a distributed manner. Being a peer-to-peer network, the blockchain [22] is a promising technology for this task. It is expected to have additional advantages like verifiability, transparency, integrity, redundancy and inherent trust [44].

The research question of this paper is how to enable a coordinated behavior of distributed ESSs within an energy community based on blockchain technology and which advantages such a setup provides. To answer this with a proof-of-concept the paper is structured as follows. We propose our concept in Section 3 and describe the implementation in Section 4. Section 5 summarizes first evaluations of the system and Section 6 concludes the work and provides the further research agenda.

2 RELATED WORK

This section summarizes research activities in the field of energy communities, basics about the blockchain technology and the state of the blockchain technology in the energy sector.

2.1 Energy communities

Research activity in the field of community energy has been increasing in the past decade. Major findings are that the maximum load of secondary substations and the necessary grid reinforcement can be reduced. By exploiting tariff optimization end consumers can benefit economically as well [33]. A main challenge is to adapt the legal framework in order to enable business models [16].

Our focus is also on energy communities as locally confined areas in a low-voltage grid. In contrast to the research above we do not investigate sharing large, central ESSs for the community. Participants of the energy community accumulate their load and share their distributed assets like PV plants or ESSs like it is known from the concept of a virtual power plant (VPP). Previous research shows that by exploiting the power dependent efficiency of ESSs a reduction of losses and an increase in self-sufficiency can be achieved even with comparably small communities. An analysis of the benefits of the concept for community sizes up to 500 households concluded that the efficiency is improved by 21 percentage

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points, while a community size of five already results in 98 % of the efficiency increase [30]. So far such a behavior is not legally allowed in Germany as soon as public infrastructure is used [13].

A similar approach is proposed in [38] for centrally coordinating demand response as a service. However, in this paper we propose a new concept for a VPP without a central intermediary by coordinating distributed units in a distributed manner.

2.2 Blockchain technology

Blockchain technology is mostly known as the underlying technology of Bitcoin [22]. Apart from cryptocurrencies and other financial services it is expected to have a revolutionary potential in many other sectors as well [34]. This reputation has to be scrutinized and critically analyzed for a given application [44].

A blockchain is not a single technology but a combination of several technologies. In general it is a distributed ledger, in which lists of transactions are structured in blocks. These blocks are linked using cryptographic hash functions, which guarantee an immutability of the past. Peers of the blockchain network can modify the state by sending transactions. Consensus mechanisms ensure that the state of the blockchain network is not corrupted [17, 22, 40, 43, 44].

Blockchains can be permissioned or permissionless [44]. In permissionless blockchains anyone can participate in the network and consensus mechanisms such as proof-of-work (PoW) are needed to arrange that the state of the network is not corrupted. PoW means that computational work has to be done in order to *mine* a new block [22, 43]. Thus an attacker would need more than 50 % of the total computational power of the network in order to corrupt it. In permissioned blockchains more energy efficient concepts like proof-of-authority (PoA) [42], where only validators are allowed to *mint* (produce without work) new blocks. With PoA the network cannot be manipulated as long as 50 % of the validators are honest. Furthermore blockchains can be private or public depending on if anyone can read the data from the blockchain [44].

In combination with smart contracts many applications are possible. A smart contract is an agreement between two or more parties, encoded in such a way that the correct execution is guaranteed by the blockchain [40]. Including this concept, Ethereum [9] aims to be a permissionless technology on which all transaction-based state machine concepts can be build [43]. Other projects like Hyperledger [36] enable permissioned platforms for blockchain based applications.

2.3 Blockchain in the energy sector

Several studies recently analyzed the potential of the blockchain technology in the energy sector [1, 7, 14, 27]. Summarizing, they concluded that there is a high potential, especially for energy trading, automation of processes and new business cases.

Most of the community energy pilot projects and research focuses on different electricity markets [18–20, 23, 31]. The blockchain technology has the potential for disintermediating aggregators in energy trading [21]. Other areas of interest are in fairness-control in micro-grids [6], certification of green energy [15], charging e-cars [32] or supporting grid stability by redispatching [35].

Section 2.1 shows that there is a high potential in the coordination of distributed units, but the legal framework is not yet adapted.

As blockchain based solutions are suitable for such applications, changes in the regulatory framework are demanded [3].

We are not aware of any other current research on blockchain based organization of distributed prosumers with the aim of increasing both efficiency and self-sufficiency.

3 CONCEPTUAL APPROACH

In the proposed concept, the residual load of all participating houses is added up to a community residual load and the ESSs of the houses of the community are operated in an efficient manner considering the power dependent efficiency of the ESSs [30]. In order to achieve this, a distributed control structure, which represents the distributed nature of the ESSs, is implemented as a smart contract on a blockchain.

The general topology of our concept is visualized in Figure 1. The energy related components are highlighted in orange and the communication links in blue. For the first implementation of the proof of concept we chose a community size of four participating houses in accordance with the results from [30].

The participating houses are all located at one low-voltage feeder and they have one grid connection point for external balancing in case of over- or undersupply. As there can be houses on the same feeder, which do not necessarily take part in the community, the grid connection point might be virtual. In theory the houses could also be at different feeders, but that would be less beneficial for the EPS. The locality of the community would disappear, which might result in unwanted power flows and increased line losses. These do not exist outside of the feeder if all participating houses are at the same feeder.

Each house has an electricity demand, a PV rooftop supply and an ESS. They each have a Raspberry Pi, which controls their ESS and runs a full node of the blockchain and an interfacing software. In general not every individual house necessarily has to run a full node. Participating houses who do not run a full node have to rely on the trustworthiness of neighboring nodes.

Taking [44] into account a permissioned blockchain is suitable as all participants are known. As privacy is likely to be important to the participants the blockchain can be private, where applicable the external electricity supplier can be granted access.

For the proof-of-concept we chose to utilize a private instance of an Ethereum blockchain [5, 43] with its PoA "Clique" consensus algorithm [42]. This is not truly a permissioned blockchain as in theory anyone who knows the genesis block and blockchain id of the private chain and who has physically access to the network is able to run a node and synchronize to the network. The advantage of utilizing Ethereum is that it is open source, open to use, has a large community and is comparatively far developed and well documented. The PoA algorithm enables the nodes to *mint* the new blocks in sequence in an energy efficient manner without the need of a trusted third party.

For a real implementation of the concept it has to be ensured that only cryptographically authenticated units like smart meters with built-in private keys are permissioned to participate in the network. This is hypothesized as an assumption and not focus of this paper.

Figure 1: Concept topology with energy related components (orange) and communication links (blue)

For the coordination of the ESSs, a previously proposed algorithm [29] is implemented as a smart contract on the blockchain. The general idea of the algorithm is to only operate subsets of the total available ESSs in order to operate active ones close to their operation point with maximum efficiency and to avoid low-efficient part load operation.

As the focus of this paper is on the proof-of-concept of the distributed controller, the blockchain is implemented in wall-time in order to represent the full complexity of the blockchain technology, while the power flows are simulated as described in detail in Section 4.

4 IMPLEMENTATION

Four Raspberry Pi single-board computers are used to represent each of the four energy community houses mentioned in Section 3 and shown in Figure 1. They are interconnected by Ethernet links for TCP/IP communication. All four devices do have the same setup. Raspbian Stretch [25] is used as operating system with good support for the Raspberry Pi. Beside that, Go Ethereum (Geth) [10] runs full authority nodes of a private instance of an Ethereum PoA-blockchain with 15 s block time on each device.

A smart contract written in Solidity [10] is deployed onto the blockchain. It offers registration and deregistration of houses, sharing of ESS operating parameters, state of charge (SOC) and residual load of each house and the calculation logic of the control commands for the ESSs as described in Section 3.

The interfacing software is written in Python 3 [24] and follows an object oriented approach, which enables adaptability e.g. onto other blockchain technologies as well as extensibility for additional features. It utilizes the Web3.py library [10] and thereby JSON-RPC over HTTP [10] to interact with the Geth instance running on the same device. The internal time resolution of the software is adjustable and 1 s by default. With this frequency, house-individual values for PV generation and household load are read from time-series files. The residual load and the SOC of the ESS are written to the smart contract once per block. With every new block, these values are distributed in the network and each house's smart contract instance calculates the control command for its ESS based on the new state. The ESS is modeled in Python 3 [24] based on [28] and follows this instruction if possible. All relevant data of this procedure is written to a log file so that it can conveniently be analyzed.

Only freely available software and low-cost hardware is used for the implementation. Furthermore, the interfacing software and the

smart contract source code is published under GNU Lesser General Public License on <https://github.com/cs7org/ethome/>, making the entire setup easily reproducible.

5 RESULTS

This section firstly states the results from the first test run and secondly gives a first cost-benefit estimate.

5.1 Technical results

The first evaluation a of the proof of concept is based on a two-day test run. The ESSs are all parameterized with a net capacity of 4 kWh and a maximum power of 3 kW. Load profiles from [37] and internally measured PV profiles are allocated to each house as time-series. The general behavior of the system is visualized for a part of the second day in Figure 2 a). The residual load is visualized in red. Load respectively discharging of the ESSs is positive and PV surplus respectively charging the ESSs is negative. The powers of the ESSs are illustrated in dark blue (house alpha), light blue (house beta), green (house gamma) respectively yellow (house delta). Slightly transparent colors are used for unfulfilled ESS commands from the smart contract, fully colored areas mean that the ESS actually behaved that way. In general, Figure 2 a) shows that individual ESSs are able to self-coordinate without the need of a central controller.

Just before 13:00 all four ESSs are already fully charged and are thus no longer able to charge. However, the distributed controller still calculates the control commands. Within the black areas too much switching happens for a display of the behavior in the given resolution. For this purpose a zoom in the afternoon time is given in Figure 2 b).

It can be derived that inefficient low part load is avoided whenever possible and if necessary only a single ESS is concerned. Depending on the residual power there is always a different number of ESSs active. The SOC is kept homogeneous within the community as always the ESSs are active, which deviate correspondingly from the rest of the community. The ESS powers build step functions which cumulatively follow the residual load with a short lag of about a block time. Apart from the lag there are also short spikes of about 1 s length, which deviate from the residual load. These result from the switching process of one ESS to another ESS and the internal resolution of 1 s of the interfacing software. Thus the spikes might be shortened or cleared out by utilizing a higher internal resolution. However at larger community sizes the spikes are expected to become relatively smaller as they result from a switch

Figure 2: Overview (a) and zoom (b) of ESS behavior during the second day of the test run

from one ESS to another and are thus bounded from above by the maximum power of an individual ESS.

In order to evaluate the electrical grid load the power in the virtual grid connection of the community is visualized for the same test run in Figure 3. Figure 3 a) shows the grid connection power in the test run compared to a simulation with the same input parameters without any coordination of the ESSs. For the visualization 15 s mean values are taken in order that a clear course is pictured. Figure 3 b) shows the scatter plot for the corresponding values in 1 s resolution. Despite the produced spikes the decentralized controller results in less high peak load on the grid.

The self-sufficiency increases from 51.10 % to 59.20 % stating that the load on the grid is also reduced in terms of the energy amount in spite of both the short lag and the spikes. As expected the distributed control not only achieves a better exploitation of the SOC range but also an increase in efficiency. The total ESSs' efficiency of the test run is increased from 71.86 % without coordination to 75.56 %. These results however only represent the first test run and are not yet statistically significant.

5.2 Economic results

The total costs for the prototype system with 4 participants amounts to less than 180 €. Opposite stand the efficiency increase and the increased occupancy of the distributed assets. These equal yearly savings of 246.28 € considering an extrapolation from the test run, a feed-in tariff of $12.2 \frac{\text{ct}}{\text{kWh}}$ [12] and an electricity price of $29.86 \frac{\text{ct}}{\text{kWh}}$ [4]. This is a first estimate based on the proof-of-concept only and does not consider the actual costs for the necessary smart meters with a private key. Longer test runs and more detailed cost evaluations are necessary in order to be able to rate the consumer's capital costs. In addition to that the ideational value of an increase in self-sufficiency is obtained.

Figure 3: Overview of the virtual grid connection (a) with corresponding scatterplot (b)

6 CONCLUSION

This paper provides a proof of concept of a blockchain based distributed controller for the efficient share of ESSs in energy communities. The proposed control structure reflects the changing energy landscape. The concept itself and its technical implementation are described and published under an Open Source License. First results show that the concept is applicable and probably economically feasible. Within the test run both the efficiency and the self-sufficiency are increased in comparison to a not coordinated system.

Without the need for an intermediate, the households have the full power and visibility over the system and the full economic benefit. The blockchain enables verifiability and integrity of the energy data as well as trust between the participants. The concept is inclusive for everyone in the considered local area as even sharing of resources with trust-less neighbors is possible. There is no single point of failure.

However, the smart contract and the interfacing software still need to be improved considering privacy, automatic recognition of offline nodes and reduction of the spikes. Approaches for influencing the delay and difference between residual load and battery commands are varying the block time, the transaction timing or using moving averages as basis for the coordination. The investigation of the communication characteristics and the impact of other communication technologies is another important research topic.

The concept itself is extendable in various directions. When implemented on a public blockchain like the Energy Web [8] or in future on a sub- or parachain of it, the community can interact with other communities or utilities. Thus e.g. a provision of ancillary services by the decentralized virtual power plant becomes possible. If more sources than just PV are considered, an automated and immutable clean energy certification can be included. Additionally, the settling within the community can be automated.

Furthermore, when scaled the concept is in theory also applicable to organize different kinds of flexibility assets. A distribution system operator or other aggregator can provide a community and adapt the concept for all kinds of assets within the community. Not only the control of ESSs but also of distributed assets like power plants, e-mobility charging stations, combined heat and power units, demand response etc. is theoretically possible.

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