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Blockchain Grid

Final Report

2021

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ProjektnehmerIn (Institution)	Energienetze Steiermark GmbH
AnsprechpartnerIn	DI Dr. Gregor Taljan
Postadresse	Leonhardgürtel 10 8010 Graz
Telefon	+43 664 616 2717
Fax	+43 (0) 316 90 555-22 790
E-mail	gregor.taljan@e-netze.at
Website	https://www.e-netze.at/

Blockchain Grid

Blockchain-enabled flexibility activation for distribution grid management

AutorInnen:

Gregor Taljan
Energienetze Steiermark GmbH

Mark Stefan, Bharath-Varsh Rao, Paul Zehetbauer, Roman Karl, Ksenia Poplavskaya, Carolin Monsberger
AIT Austrian Institute of Technology GmbH

Teresa Handler
Energie Burgenland AG

Peter Stern, Stephan Willenig, Alexander Schenk, Franz Zeilinger, Albin Frischenschlager
Siemens Aktiengesellschaft Österreich

1 Inhaltsverzeichnis

2 Introduction

2.1 Project idea

New requirements on low voltage distribution grids must be fulfilled due to an increasing number of renewable production devices, but also due to the ongoing electrification of other sectors (e.g. transportation, heating). This development goes along with a paradigm shift. It becomes already visible, that a predictable consumption behaviour of grid customers which is the foundation of today's grid planning cannot be granted any more. Therefore, a shift from a blind operation of a pure primary infrastructure, which was designed to cover a worst-case scenario to 100%, to a capacity managed infrastructure becomes necessary.

Blockchain Grid is able to turn the conventional approach of most congestion management approaches for distribution grids upside down. The project does not consider how to deal with excess utilization, but rather how to make most use of remaining free grid resources (time-varying power and voltage bands) to the merit of prosumers and Energy Communities. Furthermore, it enables the local use of locally produced electricity through use-cases such as local Peer-to-peer trading and the use of a community storage system. This approach is enabled by combining Blockchain- and IoT technologies to a system which supports the future requirements of grid customers and Energy Communities. In particular, the approach is to implement a distributed Blockchain-based application that enables prosumers themselves to share free grid resources for their surplus generation and load, whereas the distribution system operator acts as a facilitator.

Technical and organizational requirements were analysed for a distributed solution in which grid customers can share free grid capacities and sell locally or store their surplus electricity generated from renewables. An additional focus was put on potential regulatory designs and the challenge to design an equal playing field for all grid participants, given that users are physically different depending on their localization within the grid. Part of the project was the design of a prototypical Blockchain-based solution, which was implemented in a real field test environment in Heimschuh, Styria.

2.2 Expected results

The expected results of the project have been defined as:

1. A solution design of a Blockchain-based platform that enables grid customers and Energy Communities to share free grid resources and sell locally or store their surplus electricity generated from renewables.
2. A successful implementation in a real field environment in Heimschuh with approx. 200 passive and 15 active customers.
3. A proof of concept for a Blockchain solution combining grid management with customer flexibility and use of a community storage system.

4. Recommendations for regulatory and technical guidelines for potential future Blockchain solutions in cooperation with other sub-projects in the Energy Model Region Green Energy Lab
5. A scalability and replicability analysis of the use cases

3 Use Cases

In the following subsection, the addressed use cases of the project are described. These are "Self-consumption optimization", "Energy Sharing" and "Grid Capacity Management", whereas the first two use cases are very similar, but with different ordering of the process steps. Furthermore, an overview about the user groups and their community participation is given below.

3.1 User Groups

Figure 1 shows a schematic overview of a small low voltage grid consisting of different user groups, which will be described in detail afterwards:

- Local Grid Community
- Renewable Energy Community
- Local Family Community

Figure 1: Overview about users and communities in Blockchain Grid

3.1.1 Local Grid Community (LGC)

All participants being supplied by one transformer (grid level 6 and 7) are members of the local grid community, both active and passive. A passive member is using only the base load. Active means that they also have controllable loads like a charging station, an electrical boiler, or controllable generation devices. A passive member can become an active member when he/she installs a controllable high-power device.

<u>Primary goals:</u>

- Optimization of grid-capacity utilization (based on physical aspects)

3.1.2 Renewable Energy Community (REC)

All, or a subset of LGC participants can be members of the Renewable Energy Community (REC). Additionally, REC members can form a Local Family Community (see Section □) which supports special pricing for energy transactions.

<u>Additional goals:</u>

- Utilization of community battery as energy buffer for time shifted energy trading
- Optimization of self-consumption (including dynamic allocation of battery storage)
- Peak power buffering (EV charging)
- Provisioning of accounting information for calculation of fees for local grid utilization

3.1.3 Local Family Community (LFC)

The local family community is based on a special agreement between family members to share self-produced energy for a special price (but could also be € 0.00/kWh). The members must be participants of the Renewable Energy Community.

<u>Additional goals:</u>

- Energy price: € 0,00 between members of same LFC

3.2 Use Case I: Self-Consumption Optimization

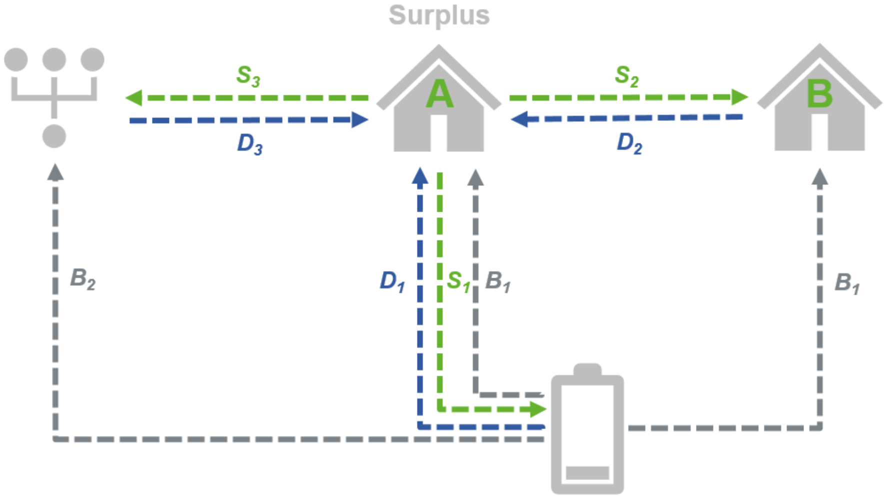


Figure 2: Focus on self-consumption optimization. S_i, D_i, B_i represents surplus, demand, and automated battery discharge after a dedicated time (e.g., after 24 hours). Index i represents a time step.

The battery will mainly be used for self-consumption optimization. Only further surplus will be offered for peer-to-peer energy trading. Figure 2 shows an example, consisting of the following steps:

Assumption: Customer A and B are participants within the same REC. In the following, the sequence of the use case is described in detail.

1. (B_1): The stored energy of customer A from the battery (from a previous instant in time) is released after a dedicated time (e.g., after 24 hours) and can be consumed by the customer itself or by other community customers with demand.
2. (B_2): Afterwards, the stored energy of customer A from the battery (from a previous instant in time) is released after a dedicated time (e.g., after 24 hours) and will be fed into the grid.
3. (S_1): If customer A has surplus, it is fed into the community battery for later re-use.
4. (S_2): If customer A has further surplus, it is sold to other community customers (e.g., if battery cannot be further used due to charging power restrictions or due to high state-of-charge) – LEC customer first (e.g., with energy price 0.00 €/kWh), REC customers afterwards (with defined community price).
5. (S_3): If customer A has further surplus (after using the battery and selling it within the community), it is fed into the grid.
6. (D_1): If customer A has demand, the stored energy is taken from the battery to serve the own-consumption.
7. (D_2): If customer A has further demand, energy is bought from other REC customers to serve the own-consumption.
8. (D_3): If customer A has further demand after using its own energy from the battery and buying within the community, energy is used from the grid.

3.3 Use Case II: Energy-Sharing

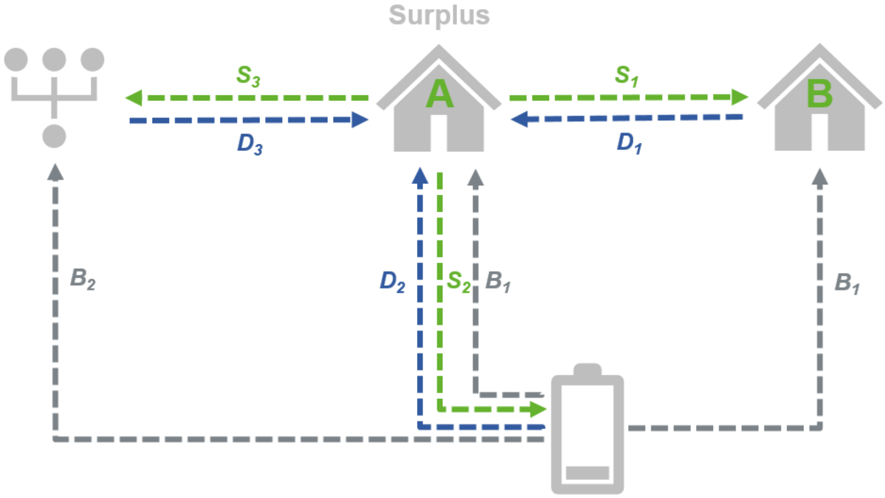


Figure 3: Focus on peer-to-peer energy trading. S_i, D_i, B_i represents surplus, demand, and automated battery discharge after a dedicated time (e.g., after 24 hours). Index i represents a time step.

The focus will be on energy trading within the community. Figure 3 shows an example consisting of the following steps:

Assumption: Customer A and B are participants within the same REC. In the following, the sequence of the use case is described in detail.

1. (B_1): The stored energy of customer A from the battery (from a previous instant in time) is released after a dedicated time (e.g., after 24 hours) and can be consumed by the customer itself or by other community customers with demand.
2. (B_2): Afterwards, the stored energy of customer A from the battery (from a previous instant in time) is released after a dedicated time (e.g., after 24 hours) and will be fed into the grid.
3. (S_2): If customer A has further surplus, it is sold to other community customers – LEC customer first (e.g., with energy price 0.00 €/kWh), REC customers afterwards (with defined community price).
4. (S_1): If customer A has further surplus, it is fed into the community battery for later re-use.
5. (S_3): If customer A has further surplus (after using the battery and selling it within the community), it is fed into the grid.
6. (D_2): If customer A has demand, energy is bought from other REC customers to serve the own-consumption.
7. (D_1): If customer A has further demand, the stored energy is taken from the battery to serve the own-consumption.
8. (D_3): If customer A has further demand after using its own energy from the battery and buying within the community, energy is used from the grid.

3.4 Use Case III: Grid Capacity Management for peer-to-peer Local Energy Communities

3.4.1 Definition

In recent years, local energy communities (LECs) are gaining interest in Europe and the world by introducing new regulations for its formation, operation and control. LECs' introduction is due to increased distributed renewable energy sources (DERs) and new loads such as electric vehicles, storage and heat pumps, hereafter referred to as nextgen loads, in low voltage distribution grids. This is to motivate the local generation, distribution, consumption and trading of energy.

Figure 4 represents a general schematic of a local energy community in a low voltage distribution grid. The most significant limitation of a local energy market associated within an LEC is the availability of a settlement process. Such processes are in place to ensure no violation occurs in the grid when the bids, accepted in the market, are executed. The need is due to the lack of controllability of DERs and next-gen-loads.

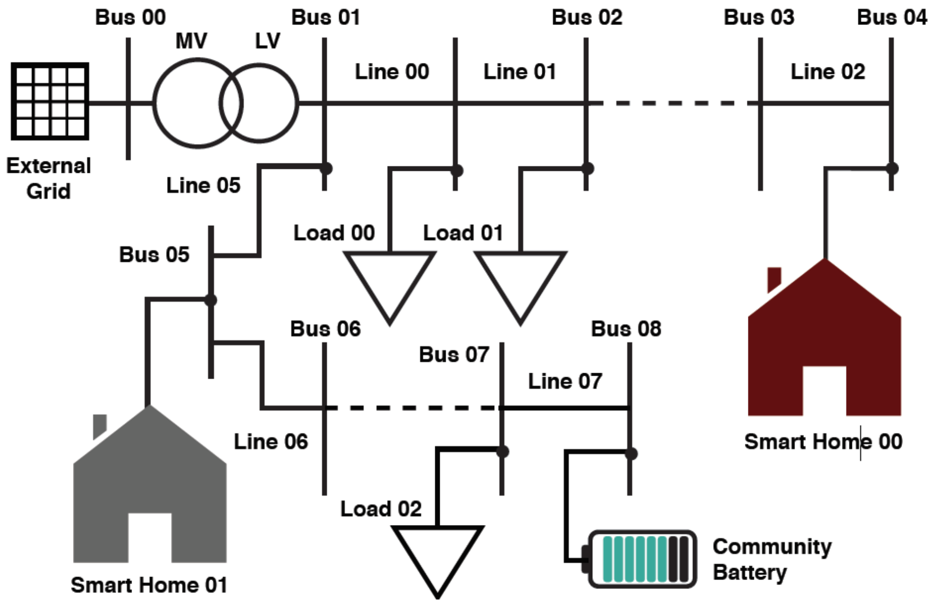


Figure 4: General schematic of a local energy community consisting of a low voltage distribution grid with various buses and lines connecting each other. It consists of uncontrollable loads, smart homes and a community battery.

GCM directly addresses the market settlement issue for a local energy community.

Grid Capacity Management (GCM) is defined as the amount of power fed-in or consumed at a bus without causing voltage violations at all buses in the grid.

The goal is to promote the local use of energy by minimizing power consumption from the medium voltage distribution grid by local energy trading. Customers in the community need to know the amount of power that they can consume or feed-in at their point of common coupling in order not to cause grid violation.

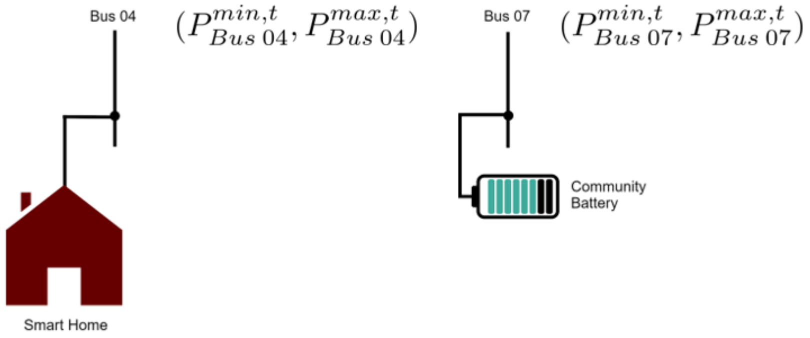


Figure 5: Limiting profiles for smart homes 01 and 02 (Only smart homes 00 shown in this figure).

The market settlement process is performed preemptively by calculating the active, reactive power consumption and infeed limits to determine the amount of flexibility that can be accommodated at various controllable buses [1]. By doing so and constraining the flexibility at those buses based on the generated limits, grid violations can be eliminated. This can be observed in Figure 5 where limiting profiles are generated at the points of common couplings of flexibilities. It is known that power grids are non-linear and non-convex in nature. In order to determine the limits at controllable buses in the grid, the GCM uses a heuristic optimization technique using genetic algorithm and Holomorphic Embedding Load Flow method.

3.4.2 Stratified Control Scheme for Low Voltage Distribution Networks

One of the major developments within the BlockchainGrid projects is a stratified control scheme [2]. It is developed for voltage management in a three-phase low voltage distribution grid, as part of an LEC. LV grids are inherently unbalanced, and the unbalance is further increased by DERs and next-gen loads. It is paramount to minimize it for safe system operation. A methodology to generate optimal set-points at a certain number of controllable buses at critical nodes is presented. Flexibilities connected at these buses actively track these set-points using model predictive control.

In this research, smart buildings with various flexibilities, such as electric storage and heat-pumps, are connected at these critical nodes. The upper level controller consists of an optimal power flow model using a three-phase unbalanced holomorphic embedding load flow method (HELM-OPF), characterized in Section 7.5.2 and mixed-integer quadratic programming model predictive control (MiQ-MPC). Figure 6 describes the control structure.

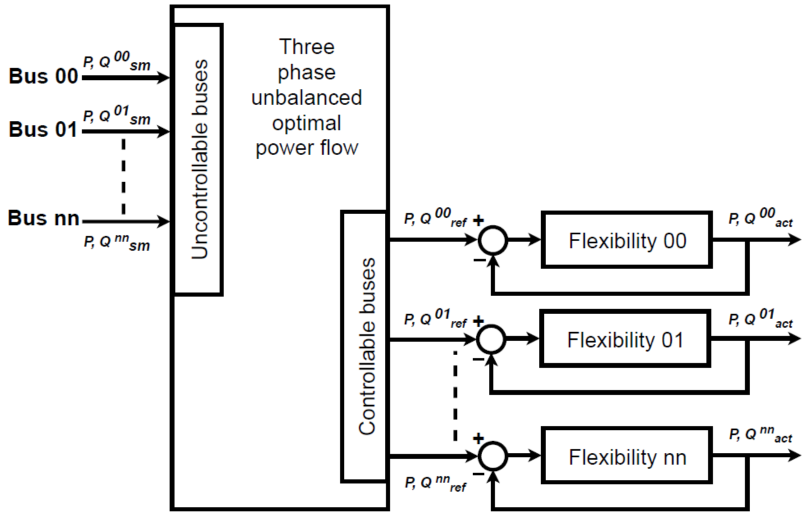


Figure 6: Structure of the stratified control scheme. Inputs to the grid controller are forecasted profiles of smart meter active and reactive (Psmi, Qsmi) profiles from loads located at various uncontrollable buses (Bus 00, Bus 01, …, Bus nn). Outputs are optimal P refi and Qrefi set-points that are calculated using HELM-OPF and fed into individual flexibility controllers. Using these reference profiles, the flexibility controller produces optimal set-points for its flexibility portfolio, which are Pacti and Qacti using MiQ-MPC. Based on the available flexibility type and their sizing, the buildings may not be able to perfectly tract the reference profiles generated by the grid controller

3.4.3 GCM and Machine learning models

Since GCM with complete implementations of HELM-OPF is computationally expensive, a machine learnt version has been deployed in Heimschuh pilot.

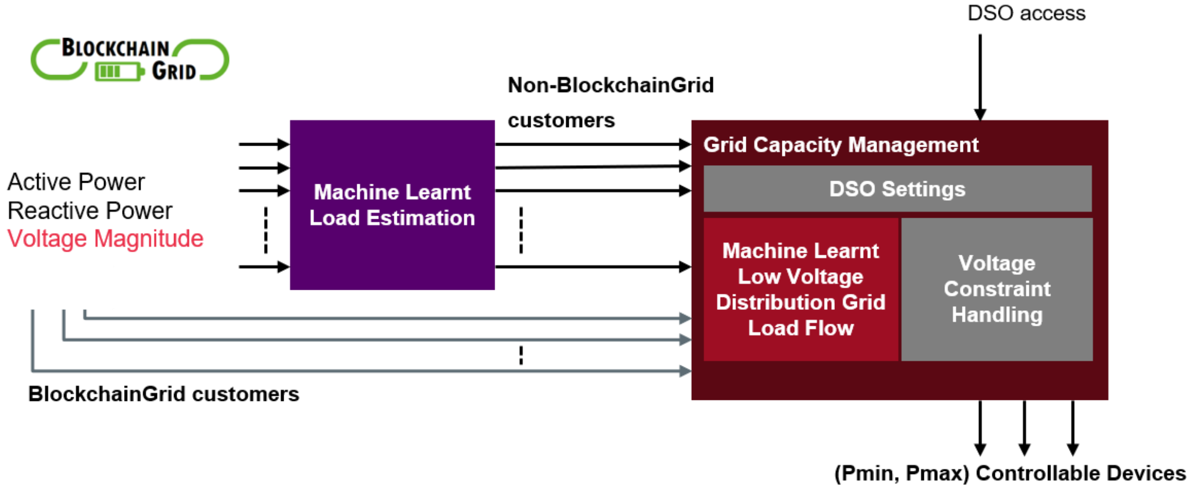


Figure 7: Schematic of machine learnt GCM

As Heimschuh is not completely observed with smart measurement devices at all the buses in the feeder and load flow needs measurements from all the buses, a novel Load Estimation method was developed using deep neural network with an average deviation of ~8 kW deviation (75th percentile ~2 kW).

Additionally, to increase the computation speed of the load flow, a major bottleneck, machine learnt load flow methods were developed. A deep neural network was trained to behave like a HELM load flow solver with an average deviation of ~0.02 pu. voltage deviation (75th percentile ~0.003 pu).

Additional modules like DSO settings and voltage constraints were developed based on the recommendations of the DSO. Figure 7 represents all the machine learnt GCM modules.

This system is currently running in the pilot and directly controls various flexibilities, making this first of its kind in Europe where an artificial intelligence is controlling grid and flexibility assets.

4 Architecture

4.1 Concept

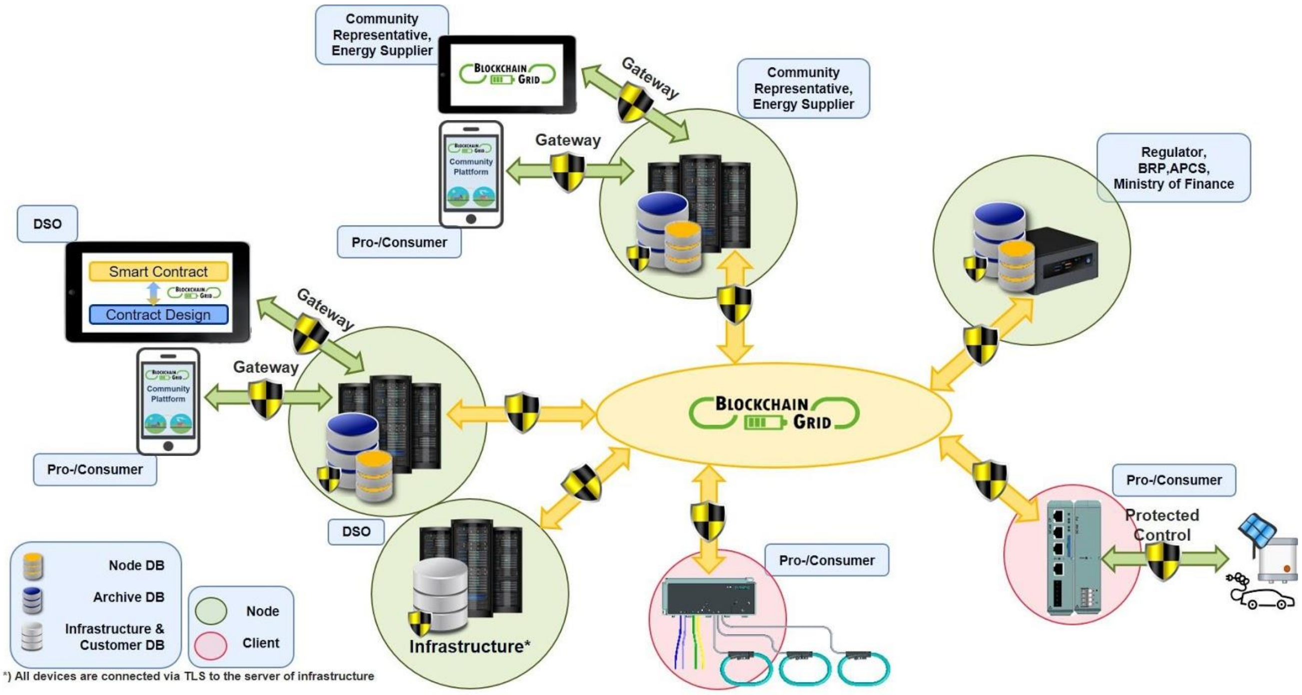


Figure 8: Blockchain Grid Architecture

Core element of this concept is a permissioned public Blockchain, based on Parity Ethereum. In principle, anyone can access the Blockchain, but the participants who can write data are limited and defined by the platform operator (infrastructure server). The written data should be stored in encrypted form. This ensures that nobody, except authorized participants, can read the data.

The consensus algorithm for new blocks is the "proof of authority" procedure, in which authorized participants (so-called "sealers") can generate blocks with transactions into the Blockchain. Participants can also be added or removed dynamically by the platform operator. This is necessary because in the "proof of authority" process the sealers generate the blocks in a defined sequence and if one sealer fails, the block is only generated by the next sealer.

There are two different type of nodes, the sealer which is allowed to generate blocks and the full node which is not allowed. Both of them have the complete image of the chain.

Embedded Systems like measuring devices and other sensors or actuators are connected to the Blockchain as clients. These clients do not keep any image of the blockchain, but sometimes control information are necessary (e.g. for controlling a charging station for electric vehicles). This is also done via a protected connection and should be possible also via slower communication protocols like CDMA (minimum 3G).

A special feature is to start a new chain after each accounting period. This is triggered by the infrastructure server. The first transaction stores any necessary information of the old chain, like the hash value from the last block. This serves as a manipulation safeguard of the old one, which is archived in a database on the nodes. A deletion of the archived data can also be initiated by the platform provider. The chosen implementation complies with the principles of data minimization and memory limitation since data is stored on the Blockchain for only one accounting period. This facilitates the enforcement of the rights of rectification and cancellation according the General Data Protection Regulation GDPR.

The infrastructure server is operated and maintained by the platform operator. Information for the Blockchain, smart contracts, configuration and roles of the participants as well as the access rights to data are stored on this server. The real customer data (name, address, customer number) is also assigned to the ID within the Blockchain. This assignment is managed and used by the Distribution System Operator (DSO) to transmit billing-relevant information. In this way, the platform operator represents the person responsible in terms of data protection law, which is the only one who can access the server. The data exchange between the infrastructure server and the participants takes place via an encrypted connection (TLS).

In order to be able to access the data, each participant receives an access identifier (username and password). This identifier is linked to the customer data by the infrastructure server. Each node provides a way to login with your access ID and obtain data according to their access rights (so called Gateway). The username and password are queried and validated via the node at the infrastructure server, which notifies the node of the Blockchain ID and the role and access rights of the participant. In order to strengthen the relationship of trust between the participants and the nodes, the participant can determine which nodes he wants to connect (see “7.4 Dashboard/User Interface”).

4.2 Smart Contract

There was one smart contract developed which is responsible for three things:

1. calculating the transfers in the energy market (for the REC and the LFCs)
2. calculating values for controlling the community battery
3. communicating with the GCM and respect its results in 1. and 2.

The routines connected to 3. are loosely coupled in order to be able to use the smart contract without the GCM as well. From the perspective of the smart contract there are different roles of actors, including several prosumers, a battery controller, an infrastructure server and the GCM. An actor is usually identified by the address of its associated Ethereum account. The trading algorithm follows a fixed set of rules and is part of the smart contract. Each prosumer can configure its trading behaviour, e.g. either prioritise self-consumption or prioritise the peer-to-peer trading.

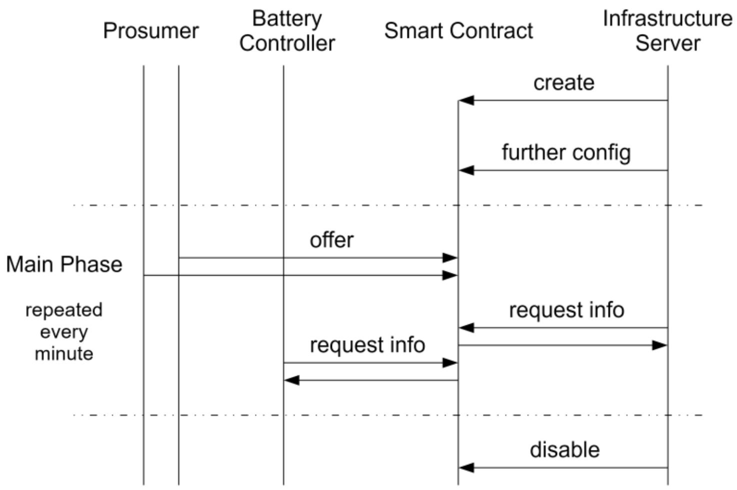


Figure 9: Smart contract interaction

The smart contract is written in Solidity, which is the most widely used high level language for Ethereum smart contracts. We do not use Ethereum's native currency Ether in payments for the energy, but there is an accounting based on Euro taking place.

There can be multiple instances of the smart contract. It is intended that one instance is active for one month after which it will be deactivated and followed by a new instance for the next month. The lifecycle of one instance consists of a start phase, the main phase and the inactive phase. In the start phase, the smart contract is deployed and configured. The main phase is further separated into timeslots, in which the trading rounds take place. We chose one minute as the duration of one timeslot.

Each prosumer sends once in a timeslot the values of produced and consumed energy. There are mechanisms in place to handle communication outages and delays. If the smart contract receives no or wrong messages from one prosumer, this prosumer won't be able to participate in the specific trading round, but won't have any further disadvantage.

At the end of each trading round there will be results that describe all the computed energy flows including the trading costs. The battery controller should fetch the resulting charging power each timeslot any charge or discharge accordingly. The results are also delivered to a database where further evaluations can be performed.

The grid capacity management (GCM) itself is not taking place on the blockchain, but it has an impact on the calculation of the peer-to-peer trading. Therefore, the smart contract provides additional functionality for the GCM. Connecting the GCM is optional, which means that the peer-to-peer trading can either be run on its own or in combination with the GCM.

From the perspective of the smart contract the additional functionality for the GCM brings three new roles. There are points of measurements, which provide measurement data for prosumers and other important points in the grid. The GCM should regularly collect the measurement data and then again send the results of its computation to the smart contract. At last, there can be charging stations or other controllable devices, that request limits from the smart contract which they should respect.

4.3 Key Performance Indicators (KPIs)

One of the project targets was an evaluation of Blockchain technology as base technology for solutions for future energy communities roughly defined in EU directives (Clean Energy Package, Green Deal). The result was that the implementation of several functional requirements is economically not feasible or impossible. Based on practical experiences the following 4 solution concepts were identified and compared (see Table 1). This comparison was used to develop and suggest potentially optimal solution approaches described later in this document.

Private Blockchain

This concept is used for the field test in this research project. It is based on a "Parity Ethereum" Blockchain (Private / Permissioned) with a proof of authority consensus algorithm. There is a separate blockchain in each microgrid (all prosumers and consumers within one transformer station) and all the data is stored in a monthly blockchain. So, a new chain is started after each accounting period due to privacy reasons. It's possible to use a private blockchain also with no transaction fees, because the wallet can be refilled from the admin and there are no dependencies to a real crypto currency. In the blockchain are running decentral smart contracts for some algorithm. The privacy is controlled by user roles which are defined by the system operator.

Public Blockchain

The public blockchain is also based on a "Parity Ethereum" Blockchain (Private / Permissioned) with a proof of authority consensus algorithm, but it is not possible to stop and restart on a monthly base. There is an existing infrastructure and therefore every transaction needs a transaction fee and some cost for the execution of the algorithm. So, it is not designed for a big amount of data or control algorithms. Some data are stored in a central cloud and only secured via hash in the blockchain.

Central IoT

The IoT is a more established technology and so at the moment there are more possibilities for the architecture. The central IoT should represent a central cloud server where the algorithm is running, and the embedded devices are connected with standard IoT protocols (like MQTT). There are few maintenance costs and efforts needed.

Decentral IoT

The difference in the decentral IoT is a controller in every microgrid, to handle the control algorithm locally and only deliver concentrated data to the global cloud. So, it is independent to the other microgrids and if there are any errors it will not influence the other ones.

Table 1: Comparison of different technologies

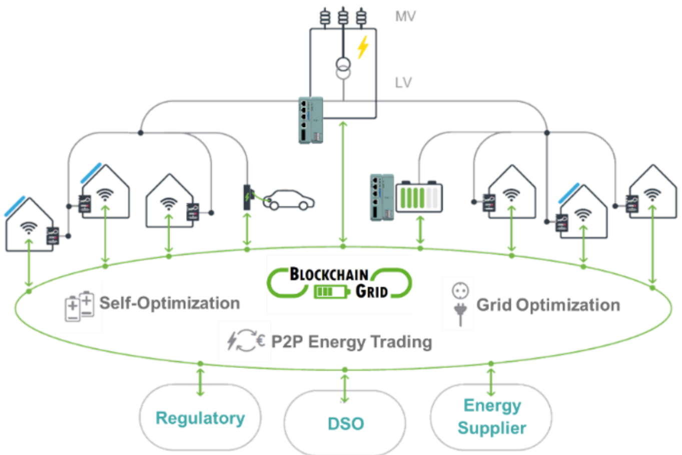
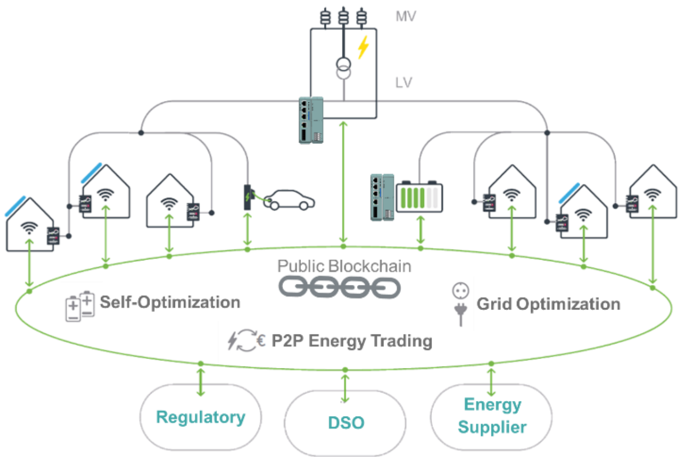
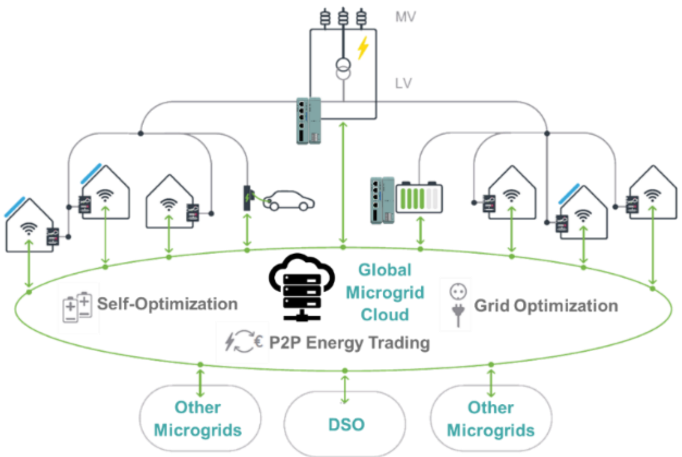
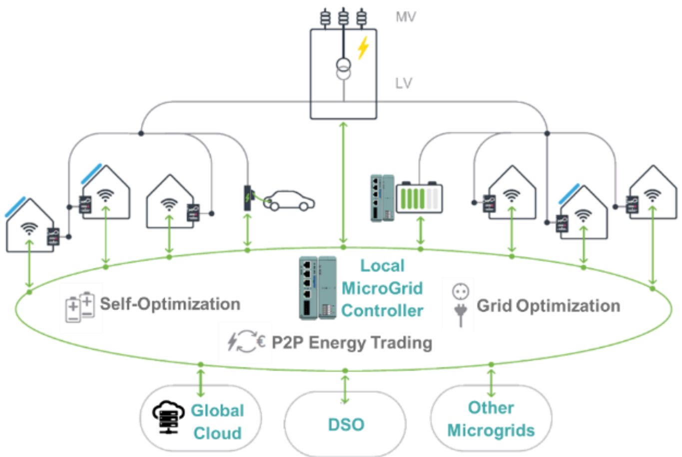
Private Blockchain	Public Blockchain
	
Central IoT	**Decentral IoT**
	

Table 2 gives an overview about several Key Performance Indicators and their evaluation on the four different architecture concepts. The colour (red, orange, green) indicate the qualitative result (bad, middle, good), the direction shows the quantitative result (e.g., high, middle, low).

Table 2: Comparison of different Key Performance Indicators

	Private Blockchain	**Public Blockchain (EWF)**	**Central IoT**	**Decentral IoT**
Practicability	→	↘	↑	↑
Product maturity	→	↘	↗	↗
Costs (CAPEX)	↗	↘	→	→
Costs (OPEX)	↘	↑	↘	↘
Access	Private	Public	Private	Private
GDPR compliant	↑	→	↑	↑
Protocol	Blockchain Parity Ethereum PoA	Blockchain Parity Ethereum PoA	IoT e.g. MQTT	IoT e.g. MQTT
Transparency	→	↑	→	→
Trusted Documentation	↑	↑	→	→
Tamper-Proof	↑	↑	→	↗
Functionality	→	↘	↑	↑
Possible Amount of User Data	↑	↘	↑	↑
Overhead Data for Protocol	↗	↗	↘	↘
Data Erasure	monthly	Not in Chain	Real Time	Real Time
Transaction Time	5s	5s	Real Time	Real Time
Latency	↗	↗	→	↓
Resiliency	↗	↗	↘	↗
Scalability	→	↘	↑	↗
Reliability	→	→	↑	↑
Security	↑	↑	↑	↑
Maintainability	→	→	↑	↗
Availability	↑	↑	↗	↑
Run on Embedded Systems	↑	↑	↑	↑
CPU Performance (Customer)	→	→	↓	↘
Memory Usage (Customer)	↗	↗	↓	↘
CPU Performance (Operator)	→	→	↘	↘
Memory Usage (Operator)	↗	↗	→	↘

5 Legal and regulatory aspects

At the start of project Blockchain Grid, the EU Clean Energy for all Europeans Package (CEP), was recently adopted. Among others, it for the first time in the EU energy policy introduced the concept of ‘energy communities’, new legal entities able to jointly consume, share or sell self-produced energy. These were further subdivided into citizen energy communities (CECs, Art. 16.2(11) [3]) and renewable energy communities (RECs, Art. 21.2(16) [4]). The latter lie at the core of project Blockchain grid. Although the CEP described the rights and main characteristics of such communities, a lot of more detailed questions were expected to be addressed in the national implementation documents. In Austria, the Renewable Energies Expansion Act and Package (EAG Package) was pending adoption at the time of the project end, suffering a delay due to the COVID pandemic, so the analysis presented in the project is based on the Act’s latest draft (EAG draft). The deliverable D2.2 addresses the national and EU regulatory framework in project Blockchain Grid with regard to a number of aspects relevant for energy communities and application of Blockchain technology within them:

- local energy communities
- self-generation, self-consumption, storage and sale of self-produced energy
- peer-to-peer trade
- data protection
- grid tariffs, taxes and charges
- imbalance settlement

5.1 Local energy communities

One of the main goals of the EU Electricity Market Directive (part of CEP) is to lay down the rights, strengthen protection and encourage active participation of consumers in the energy system. The establishment of CECs and RECs is meant to bring the governance of such communities effectively into the hands of local individuals, local SMEs, institutions (e.g. hospitals, schools, libraries) and local authorities. Both of them are based on local membership and governance but CECs can engage in a wider spectrum of activities and cannot be discriminated against.

The two community types overlap in a number of ways:

- **Membership:** open, independent, with voluntary participation.
- **Legal entity:** Both CECs and REC must be a legal entity of their own.
- **Governance:** RECs are required to be “effectively controlled” by their members or shareholders that are located in the vicinity of a RE project. CECs must be under control of their members or shareholders.
- **Purpose:** regardless of the type, an energy community may not have financial gain as its primary objective of their existence but instead promote environmental, economic goals for their members and local social welfare.

In the Austrian regulation, energy communities, as introduced in the EU directives, are to be enabled within the EAG package. The main differences between CECs and RECs in the Austrian context, as foreseen by the EAG draft, are described in below [5]:

Table 3: Overview about the main differences between CECs and RECs in the Austrian context.

Aspect	Citizen Energy Community	Renewable Energy Community
Membership structure	Natural persons as well as legal entities and local authorities (Art. 16b (2), draft of ElWOG amendment [5]).	Natural persons, municipalities, legal entities of public authorities in relation to local services or small and medium enterprises (Art 74 (2), EAG draft [5]).
Technologies	Limited to electricity, may include RES	Only RES
Activities	Generate electrical energy and consume, store or sell the self-generated energy. Furthermore, it can be active in the field of aggregation and provide energy services for its members, such as energy efficiency services or charging services for electric vehicles (Art. 16b (1), draft of ElWOG amendment [5]).	Generate energy from renewable sources, consume, store, or sell the energy it generates. Furthermore, it can be active in the field of aggregation and provide other energy services (Art. 74 (1), EAG draft [5]).
Proximity to the project	Not required	Required: members or shareholders must be located in the vicinity of a RES project
Network operation	Possible (Art. 17 (7), draft of ElWOG amendment [5])	Possible (Art. 75 (3), EAG draft [5])

The Austrian draft of the EAG package includes both sale and sharing of the self-generated energy, which enables both electricity trade within the community and energy sharing within a local family community proposed in project Blockchain Grid.

5.2 Self-generation, self-consumption, storage and sale of self-produced energy

On the EU level, the CEP explicitly allows and encourages all types of self-consumption from individual to collective to energy communities. In Austria, in turn, individual and collective self-generation and consumption is sufficiently regulated in ElWOG 2010 (Electricity Act), Art. 16a [12]. Renewable energy technologies for the self-supply of electricity can, according to the EAG draft [5], receive investment support or a market premium. Investment support is foreseen for small-scale PV systems (of up to 500 kW_p – still under discussion), whereas the market premium regime is open for PV systems of over 20 kW_p, whereas it is granted in a pay-as-bid auction scheme. The market premium regime, which abolished the former OeMAG (Green Energy Clearing and Settlement) feed-in-tariff, promotes direct commercialization of the produced electricity [5]. However, the draft of the amendment of the ÖSG (Renewable Electricity

Act) requires OeMAG to purchase renewable electricity at market prices from renewable generation units of up to 500 kW until 2030 (Art. 57e (2), draft of ÖSG amendment [5]).

5.3 Peer-to-peer trade

The EU Clean Energy Package can be interpreted as authorizing the sale of self-produced electricity regardless of the type of marketplace, organized or peer-to-peer (P2P). It allows renewables self-consumers to engage in “peer-to-peer trading arrangements” (Art. 21.2(a) [3]. It specifies that P2P trading implies “the sale of renewable energy between market participants <…> either directly between market participants or indirectly through a certified third-party market participant, such as an aggregator” (Art. 2(18) [3]). Some of the questions concerning P2P, however, trade remain unanswered. For instance, if active customers decide to go beyond its community and sell their production directly to other consumers outside it, they would still be obliged to obtain a supplier license. The provisions of the Electricity Market Directive would imply that supplier obligations apply. Keeping in mind the primary non-commercial goal of energy communities, it is unclear whether community members would be motivated to engage in active energy trading.

Blockchain technology can be used in for P2P trading, as demonstrated in this project, since it can facilitate transparent and almost-immediate transactions and settlement among the participants with the help of so-called Smart Contracts. In general terms, contract law is described in the Rome-I Regulation applicable in the entire EU, which regulates contract conditions and obligations in the civil and commercial law. In fact, there is no consensus of what a Smart Contract is and whether it should be regarded as a contract in a traditional sense at all. The latter will have deep implications for the responsibilities and liabilities of those involved in the trade using Smart Contracts. For instance, [6] defines it as “a *software-based contract* in which various contractual conditions can be fixed" This implies that as soon as a condition stipulated in an algorithm is fulfilled, the contract with predefined contents is concluded automatically. In contrast, according to the founder of Ethereum, ‘a smart contract is a *computer programme* that directly controls some digital asset’ [7], i.e. token, which means that a Smart Contract is rather a self-executing *piece of software code*, which only exists in the digital environment and may create an issue of it not being fully intelligible to the contracting parties [8]. It is therefore not exactly clear whether a Smart Contract can be treated as an actual contract in the legal sense of the word. The main differences between a traditional contract and a Smart Contract are summarized in Figure 10.

Traditional contract	Smart Contract
• Main goal: to conclude legally enforceable agreements and obligations	• Software-based: Algorithms ("when x, then y")
• Can be modified	• Non-modifiable → better option for short-term contractual relations when there is potential need to adjustment
• Clear procedures for dispute settlement	• Action in case of a breach of contract, dispute settlement is complicated

Figure 10: Main difference between a traditional contact and a Smart Contract.

In Austria, the EAG package shall – for the first time - allow P2P trade, yet only *within* energy communities. The P2P trading is limited though in the manner that the surplus electricity can only be sold to the community and not to individual customers. The total electricity generated in the community is then allocated to consumers either with the static or with the dynamic key. The draft of the law also foresees that the consumption and supply of electricity generated by a community generation unit or *within* an energy community does not require a supplier status (Art. 7 (1), draft of ElWOG amendment [5]). However, the question remains whether P2P trading outside of a community or between various communities should be deemed as supply and force the community members to become suppliers. The application for a supplier status involves significant administrative effort and costs as well as a certain level of the sector knowledge. Moreover, P2P energy trade raises the question of whether it is allowed to have multiple suppliers. This would be the case if participants of an energy community are considered suppliers in addition to the residual power supplier(s) of the community members. Based on the consumer right of a free choice of an electricity supplier, the accounting within an EC can already get rather complex if EC members have different suppliers. 'Peers' having to obtain a supplier status as well is likely to complicate the matters further.

5.4 Data protection

The main principle of functioning of Blockchain is that each participant saves and processes his own copy of the Blockchain. Since Blockchain only allows new data to be added but not the modification or deletion of old data, this, on the one hand, guarantees a high integrity of the data but, on the other hand, can open up a tension with principles of data protection and rights of those affected by the data processing.

EU General Data Protection Regulation (GDPR), the main legal document on the handling and protection of personal consumer data applicable as is in the entire EU has been in force since May 2018. In order to implement Blockchain-based solutions the question of its compliance or overall compatibility with the GDPR needs to be addressed, as long as the proposed solutions involve the use of personal data, i.e. "any information relating to an identified or identifiable natural person" (Art. 4(1) [9]). Metering data is a type of personal data in the sense of the Electricity Market Directive (Art. 23 and 20(1(f)). The mandatory

Data Protection Impact Assessment (DPIA), foreseen if the processing "is likely to result in a high risk to the rights and freedoms of individuals" (Art. 29 [9]), was conducted in the project, following GDPR (Art. 35 [9]). Data protection rules and principles in the sense of the GDPR are directly applicable in Austria.

The following two important principles have been addresses in the project:

- The privacy of the data – only the customer himself can see his/her own data
- The right for the deletion of the data on customers' demand

The blockchain concept has been set up and organized to consider both these two basic principles although the basic idea of blockchain does not support easy deletion of the data stored in the blockchain and a workaround had thus to be found. The data privacy is easier to handle on the other hand since the access rights can be properly defined by the system administrator. Additionally, the issues of data protection within the project are connected not only to the use of Blockchain in the context of energy communities but also with regard to the use of Smart Meters. The Smart Meter Requirements Regulation (Intelligente Messgeräte-AnforderungsVO 2011 – IMA-VO 2011) places technical requirements on Smart Meters, such as reading customer consumption data every 15 minutes and storing them for a maximum period of 60 days [10]. Nothing in the Regulation would preclude the network operator from reading meter data with a higher time granularity, e.g. every minute, as applied in the project. However, Since January 2018, Austrian consumers concerned about the use of their personal data in Smart Meters are allowed to decline the installation of a Smart Meter explicitly.

5.5 Grid tariffs, taxes and charges

Grid tariffs, taxes and charges are one of the areas that are not harmonized on the EU level as this area remains within the jurisdiction of the individual Member States. The EU regulation rather addresses the issue of grid tariffs and tariffs methodologies from the point of view of its high-level principles of non-discrimination and the level playing field. In this vein, the Electricity Market Regulation emphasized the need for network charges to reflect the actual network costs in a transparent manner as well as the need to encourage network operators to make use of the cost-efficient an innovative solutions and flexibility [11].

In Austria, electricity that is consumed *behind the meter* is exempted from all grid tariffs, taxes and charges. This also applies to multi-apartment buildings with community generation units since the 2017 amendment of ElWOG 2010. For energy communities, in contrast, the use of the public network is explicitly foreseen and therefore special conditions concerning grid tariffs are outlined in the draft EAG package. Besides ElWOG, the SNE-VO 2018 (Electricity System Charges Regulation), last amended in 2021, sets the applicable network charges. Users of the public electricity grid (consumers and/or producers) need to pay the following grid tariff components:

- grid use tariff (paid by consumers),
- grid losses tariff (paid by consumers and producers, latter > 5 MW),
- grid access tariff (one-time cost, paid by consumers and producers),

- grid availability tariff (one-time cost, paid by consumers),
- system service tariff (paid by producers > 5 MW),
- metering charge (paid by consumers and producers) and
- a charge for other services (paid by consumers and producers).

Besides the grid tariffs, all producers of electricity as well as all electricity consumers are subject to the electricity levy, according to Article 1.1(2) of the Electricity Levy Act, including the consumption of self-produced electricity exceeding a pre-defined limit (there exists no limit for self-generated PV electricity).

Concerning renewable energy communities, the EAG draft foresees tariff reductions on the energy-component of the grid use tariff (Art. 52 (2) lit. a of the draft of the ElWOG amendment). Higher reductions are expected for energy communities located at the low-voltage grid level only, in contrast to communities including the medium-voltage grid level (Art. 75 (1), draft of EAG [5]). These two grid areas are called 'local area' ('Lokalbereich') and 'regional area' ('Regionalbereich') in the EAG draft (Art. 75 (1)). Concerning the power component of the grid-use tariff, the quarter-hour power drawn from the public grid at the metering point shall be reduced by the power from the REC (Art. 52 (2a), draft of ElWOG amendment [5]).

Additionally, an exemption from the contribution to the renewables support scheme is specified in the EAG draft (Art. 71 (5)), whereas a possible exemption from VAT has so far only been communicated through ministry staff or energy suppliers (e.g. [12], [13]). The additional exemption from the electricity levy for electricity that is generated, traded and consumed within the renewable energy community is so far fixed only for PV electricity and applies only to the amount of electricity that can be attributed to the consumption of a member on an annual basis (Art. 2(1) of the Electricity Levy Implementation Ordinance) [14]). Electricity levy exemptions for renewable electricity from other sources than PV generated and traded within a renewable energy community are foreseen but not directly covered in the EAG package. However, it is important to point out that all tariffs, charges and tax reductions are expected for electricity generated and consumed only *within* a REC, whereas remaining consumption would be subject to regular tariffs and taxes.

5.6 Imbalance settlement

Balancing responsibility implies financial responsibility for imbalances caused by deviations from submitted generation and/or consumption schedules. This responsibility can be fulfilled either directly by so-called balance responsible parties (BRPs), other entities acting as one or indirectly through another market participant. The latter is the case for most consumers, whose supplier takes over balancing responsibility for them. Until recently, most variable RES were exempt from balancing responsibility. Yet, the CEP postulates that all actors and generation technologies must be balancing responsible or delegate their responsibility to another party (Art.5 [11])[1]. This includes variable RES, active customers and energy communities. The same requirement applies to those customers that own and operate a storage unit (Art. 15(a) [3]).

In Austria, all network users must belong to a balance group directly or indirectly (ElWOG Art.85 (1)). Electricity consumers or suppliers can either set up a balance group and register as a balance responsible party (BRP) or join an existing balance group (ElWOG Art. 66 (1) [15]). The first option offers the possibility to act independently but involves a much higher operational effort and transaction costs.

Even though it is a crucial topic for the stability of the electricity grid, the current draft of the EAG package does not mention the issue of balancing responsibility for energy communities. Balancing responsibility, however, is foreseen for plant operators receiving the market premium. For generation units still operating under the OeMAG subsidy regime or for new generation units that either receive an investment subsidy or sell their electricity to energy suppliers at market prices, balancing responsibility is with OeMAG or the electricity supplier (and their balancing group). Participants of an energy community do belong to the balancing groups of their residual energy suppliers, although the challenge of multiple suppliers for one energy community and the adequate sharing of balancing responsibility still remains to be clarified. It remains to be seen whether upcoming legislation will address these open issues [16] [5].

[1] Some derogations apply, such as an exemption for small-scale RES units of up to 400kW and demo projects.

6 Simulation

To investigate the potential of the developed algorithms for energy trading and self-consumption optimization, simulative studies have been performed within the project. In the following, the simulation scenarios, the used prices, community settings and finally, the results are presented.

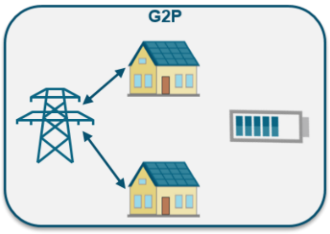
6.1 Simulation scenarios

In the following, the investigated simulation scenarios are presented. The scenario name indicates the priority of energy transactions (e.g., G2P: indicates that each customer/peer exchanges energy (demand and surplus) with the public grid/energy supply company). Thus, the following short names are used in the upcoming descriptions as well as in tables and diagrams:

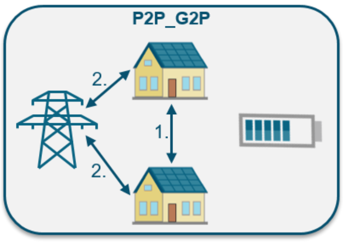
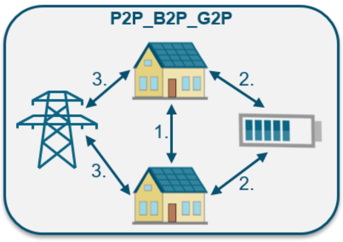
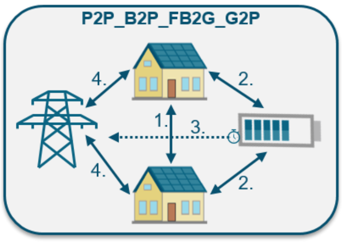
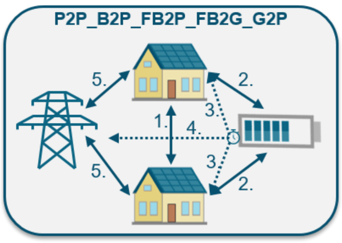
- G … Grid
- P … Peer (customer)
- B … Battery
- FB … Free battery (e.g., battery release to community customers after 14 hours and to the public grid after 36 hours)

The following subsection show the detailed simulation scenarios, whereas on the left side of the scenario overview, the components (grid, customers, battery) and their potential interaction (including priorities) is shown. On the right side, the ordering/priority of the interaction is given (e.g., first peer-to-peer energy sharing, then exchange with the public grid – for scenario P2P_G2P). First, the reference scenario is presented which could be seen as state of the art scenario where no community interaction (energy sharing) or community battery usage is considered. Afterwards, the scenarios with highest priority on energy sharing are shown, followed by the scenarios with focus on battery usage.

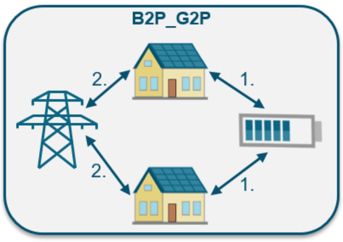
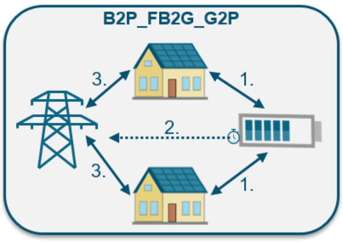
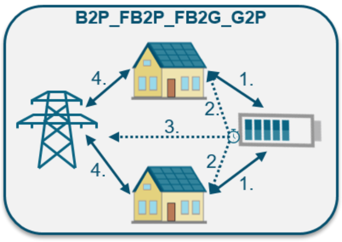
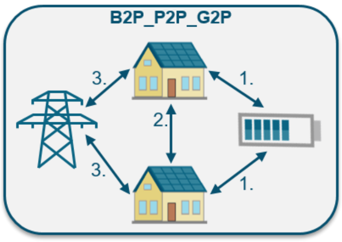
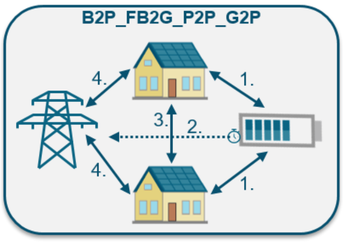
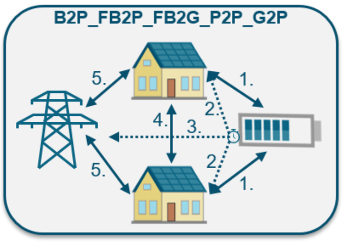
6.1.1 Reference scenario

Overview	Priorities and description
	1. From/to public grid

6.1.2 Energy sharing

Overview	Priorities and description
	1. Peer-to-Peer energy sharing (demand and surplus) 2. From/to public grid
	1. Peer-to-Peer energy sharing (demand and surplus) 2. Battery charging/discharging 3. From/to public grid
	1. Peer-to-Peer energy sharing (demand and surplus) 2. Battery charging/discharging 3. Battery release to public grid after 36 hours 4. From/to public grid
	1. Peer-to-Peer energy sharing (demand and surplus) 2. Battery charging/discharging 3. Battery release to community customers after 14 hours 4. Battery release to public grid after 36 hours 5. From/to public grid

6.1.3 Self-consumption optimization

Overview	Priorities and description
	1. Battery charging/discharging 2. From/to public grid
	1. Battery charging/discharging 2. Battery release to public grid after 36 hours 3. From/to public grid
	1. Battery charging/discharging 2. Battery release to community customers after 14 hours 3. Battery release to public grid after 36 hours 4. From/to public grid
	1. Battery charging/discharging 2. Peer-to-Peer energy sharing (demand and surplus) 3. From/to public grid
	1. Battery charging/discharging 2. Battery release to public grid after 36 hours 3. Peer-to-Peer energy sharing (demand and surplus) 4. From/to public grid
	1. Battery charging/discharging 2. Battery release to community customers after 14 hours 3. Battery release to public grid after 36 hours 4. Peer-to-Peer energy sharing (demand and surplus) 5. From/to public grid

6.2 Energy price, fees, and taxes

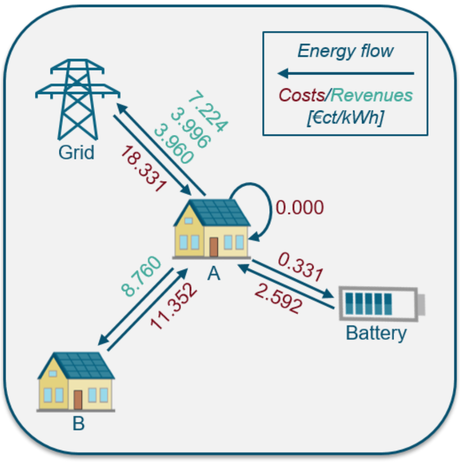


Figure 11: Overview of total costs (from perspective of customer A).

Figure 11 illustrates an overview about the potential energy flows and the corresponding total costs and revenues from the perspective of customer A (including fees and taxes). Table 4 presents the details about the composition of the total costs.

Table 4: Used energy price, fees, and taxes

Type	Energy [€ct/kWh]	Grid fee [€ct/kWh]	Loss fee [€ct/kWh]	Electricity tax [€ct/kWh]	Green electricity tax [€ct/kWh]	Biomass subsidy [€ct/kWh]	Tax [%]	Total [€ct/kWh]
Self-consumption	0.000	0.000	0.000	0.000	0.000	0.000	0	**0.000**
A → B	7.300	0.000	0.000	0.000	0.000	0.000	20	**8.760**
A ← B	7.300	1.968	0.126	0.000	0.000	0.066	20	**11.352**
A → Batt	0.000	0.210	0.000	0.000	0.000	0.066	20	**0.331**
A ← Batt	0.000	1.968	0.126	0.000	0.000	0.066	20	**2.592**
A → Grid	6.020 3.330 3.300	0.000	0.000	0.000	0.000	0.000	20	**7.224 3.996 3.960**
A ← Grid	7.300	4.920	0.315	1.500	1.175	0.066	20	**18.331**

6.3 Community Setup

The following table shows the three different community settings which have been simulated and investigated. One setting was based on the pilot customer structure in the demonstration region in Heimschuh, Styria (with 12 customer), the other two settings used 120 customers with varying capacity of the community battery storage system.

Table 5: Overview about the different community settings for the community simulations.

	Setting I	Setting II	Setting III
Number of customers	12	120	120
Number of consumption objects	12	125	125
Annual consumption	184.954 kWh	960.638 kWh	960.638 kWh
Number of generation objects (PV)	9	20	20
Annual generation	57.777 kWh	124.263 kWh	124.263 kWh
Storage capacity	100 kWh	100 kWh	400 kWh
Battery reservation time	14 hours	14 hours	14 hours
Battery release time	36 hours	36 hours	36 hours
Simulation duration	365 days	365 days	365 days
Time resolution	15 minutes	15 minutes	15 minutes

Figure 12 gives an overview about the 12 customers of Setting I. Each plot represents the average daily profile in Watt (black line), the 25-75 % quantile (yellow), and the 0-25 % and 75-100 % quantiles (red). Positive values indicate demand, negative values indicate surplus. As already indicated in Table 5, nine out of the 12 customers have their own PV production which can also be observed in the figure.

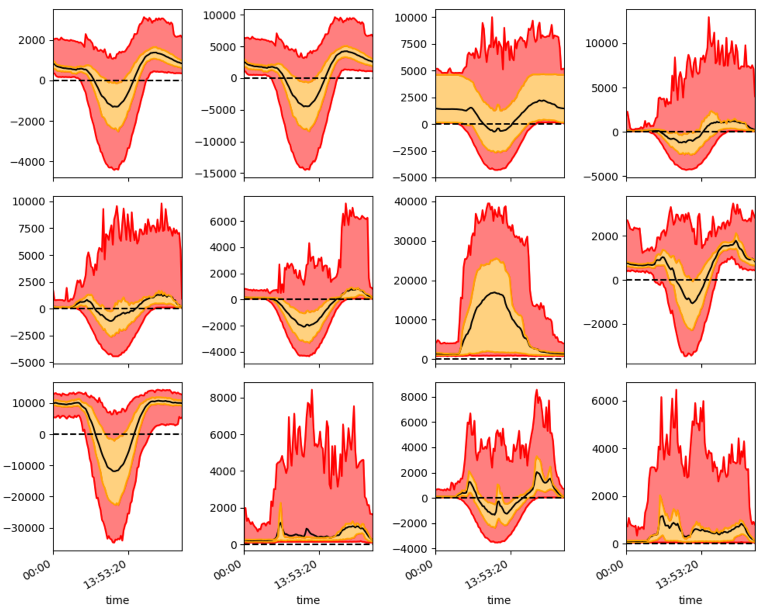


Figure 12: Customer profiles of Setting I

6.4 Simulation Results

In the following, the major simulation results are shown for a number of different Key Performance Indicators (KPIs) – some of them on community level, others on customer level.

6.4.1 PV usage (Community level)

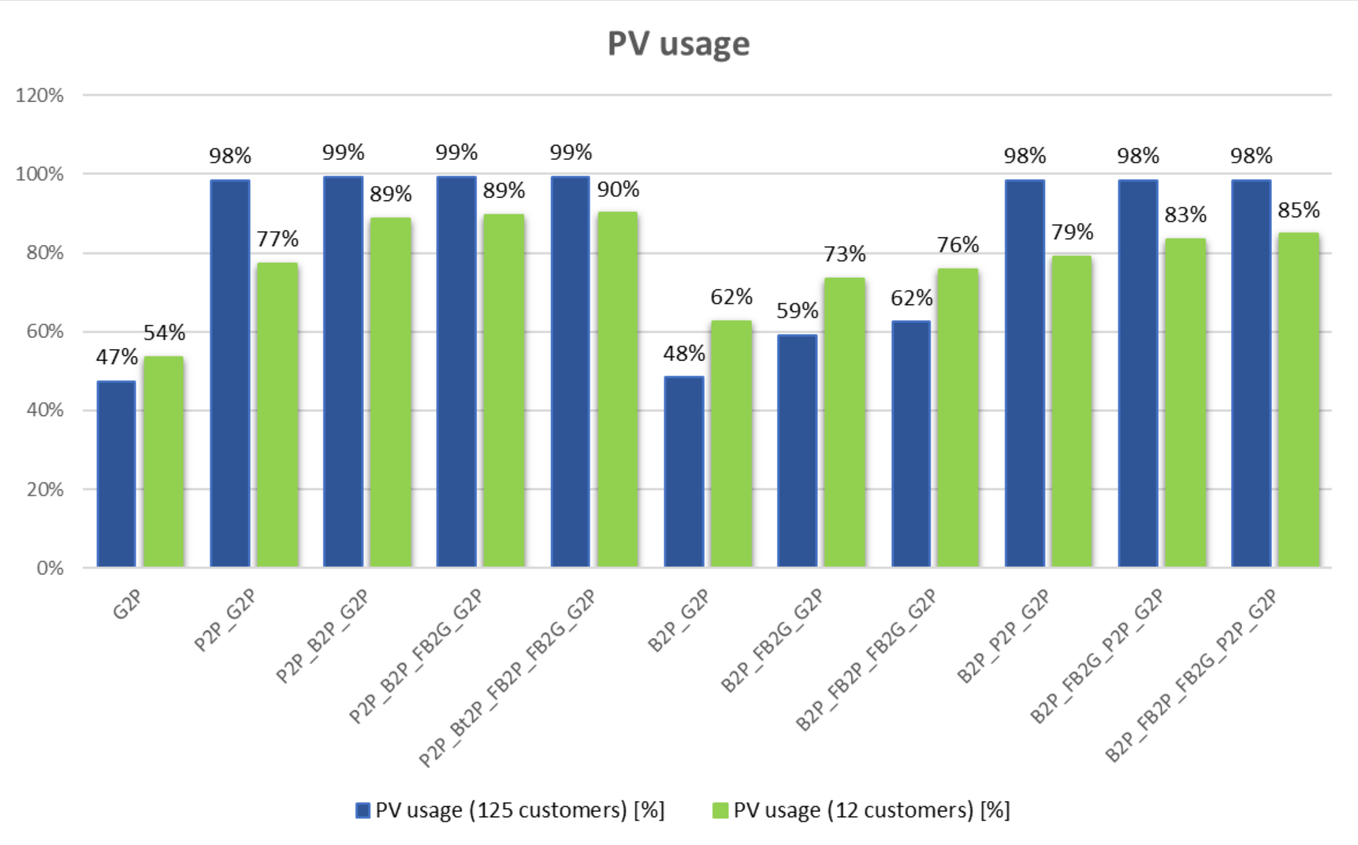


Figure 13: PV usage on community level: Comparison of simulation scenarios.

Figure 13 illustrates the simulation results for Setting I (blue) and Setting II (green) on the PV usage [%] for all 11 scenarios.

The baseline scenario (*G2P*) without any battery usage or energy sharing within the community shows that 47 % / 54 % (depending on the community setting) of the generated energy is used within the community. This share can be further increase by activating energy sharing and/or the utilization of the community storage. The best results can be achieved when focusing on energy sharing within the community (*P2P_**), followed using the storage (*B2P*) and including battery release (*FB*). In these scenarios the usage of the locally generated energy can be increased up to 90 % / 99 %. When using the battery storage as highest priority, the results as slightly lower (*B2P_**).

6.4.2 PV self-consumption (Community level)

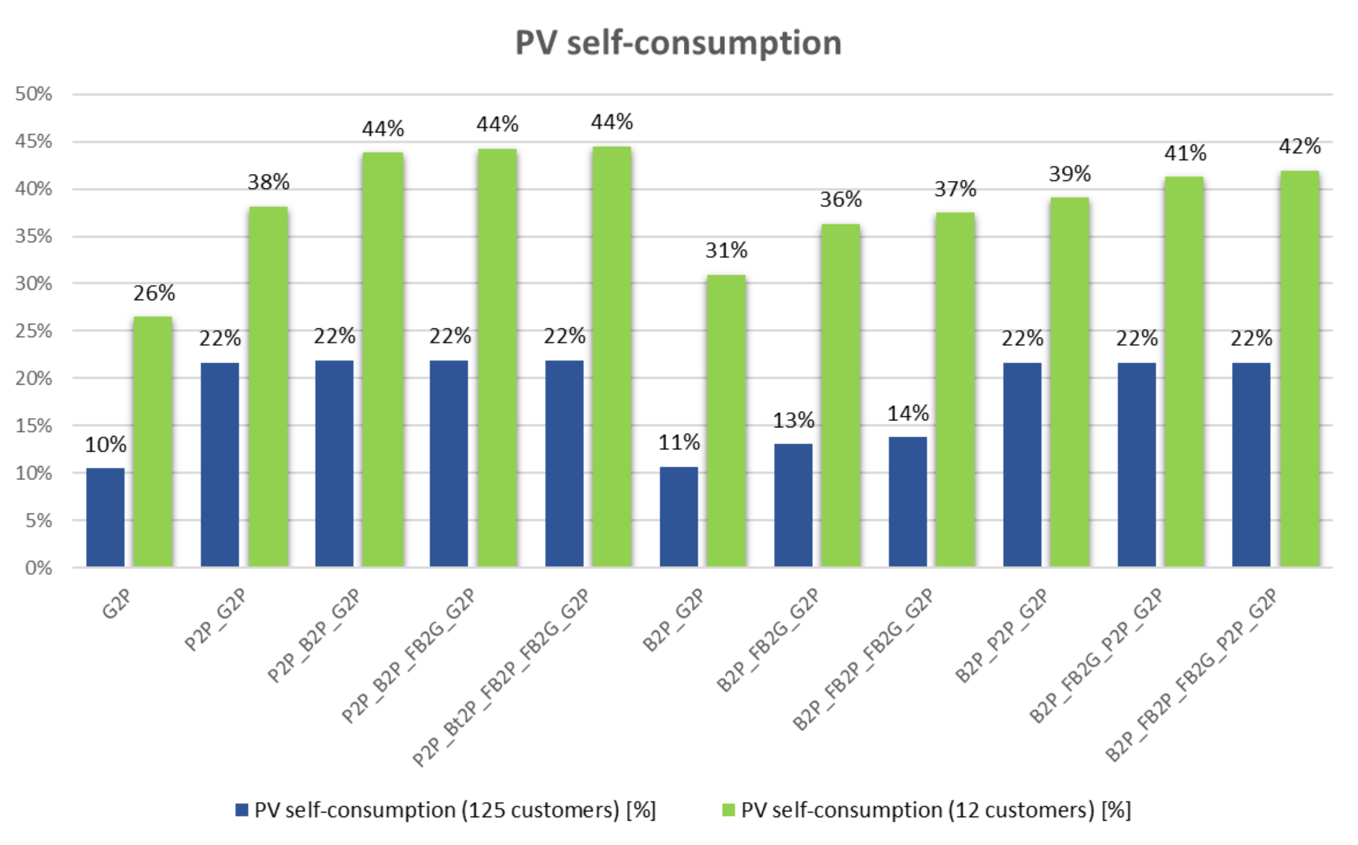


Figure 14:PV self-consumption on community level: Comparison of simulation scenarios.

Figure 14 illustrates the simulation results for Setting I (blue) and Setting II (green) on the PV self-consumption [%] for all 11 scenarios.

In the baseline scenario (G2P) 26 % / 10 % of the total community consumption is covered by the locally generated energy. This share can be further increased up to 44 % / 22 % when using energy sharing and the community storage. Similar to the PV usage, scenarios with focus on energy sharing, followed by the battery show the most promising results.

6.4.3 Reduction of CO_2 emissions (Community level)

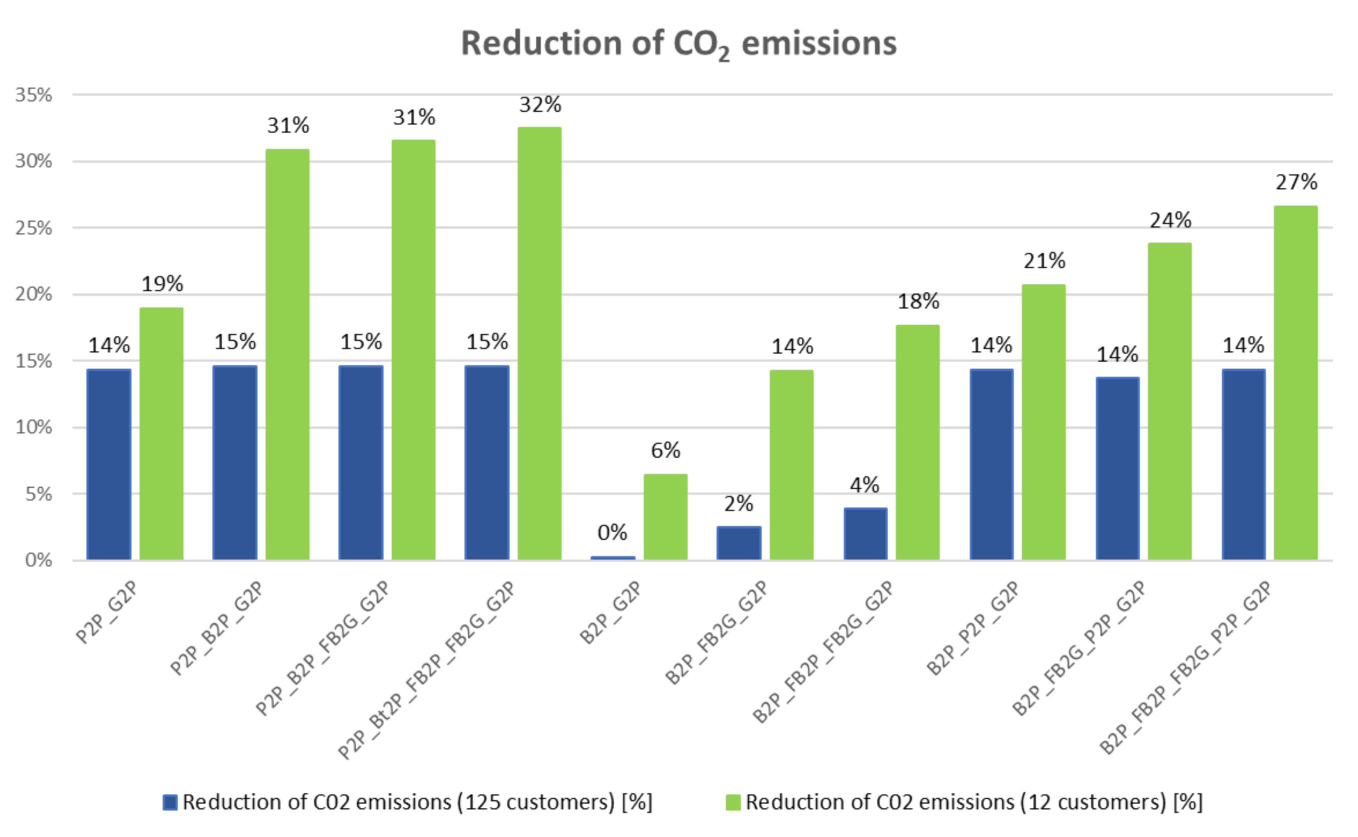


Figure 15: Reduction of CO_2 emissions on community level: Comparison of simulation scenarios.

Figure 15 illustrates the simulation results for Setting I (blue) and Setting II (green) on the reduction of CO_2 emissions [%] for all 11 scenarios.

Based on the used energy mix in the region of Heimschuh, CO_2 emission of 0,02 kg/kWh are calculated. Based on the total consumption of the energy community, total emission of about 5.000 kg / 21.450 kg have been calculated. Due to the available local PV-based generation, this amount is already reduced to 3.700 kg / 19.200 kg, which was the baseline for the comparison. Similar to the previous two KPIs, the most promising results – in terms of the reduction of CO_2 emission – can be achieved in the energy sharing scenarios, followed by utilizing the battery storage system. In comparison to the baseline scenario (G2P), up to 32 % / 15 % of the CO_2 emissions can be saved – due to energy sharing and storing.

6.4.4 Energy costs (Customer level)

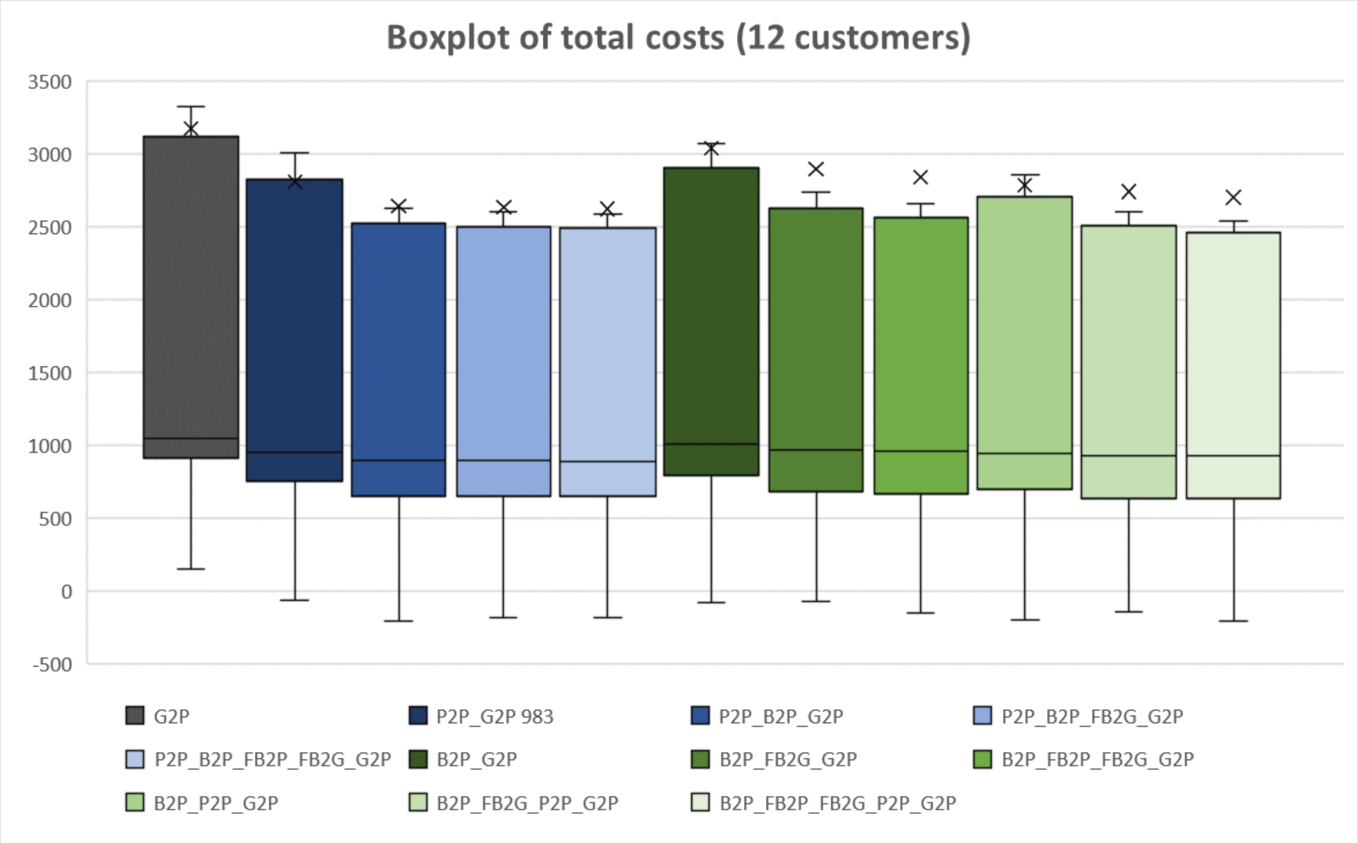


Figure 16: Comparison of total costs of the pilot customers - shown as boxplot, without outliers (2 commercial customers with approximately 11.000 € total costs)

Figure 16 illustrates the total costs of the community customers [€] for Setting I with 12 customers for all 11 scenarios.

Two commercial customers with approximately 11.000 € have not been depicted since they are considered as outliers and would reduce the readability. The costs for the customers are illustrated via boxplots for each scenario. The first bar shows the baseline scenarios (G2P) without any community interaction or battery usage. The blue bars illustrate the scenarios with energy sharing as preferred option, whereas the green bars show the scenarios with battery as preferred option. Since the commercial customers have a big impact, the average costs per customer (mean value, shown by “x”) are on top of the bars (or even above).

6.4.5 Cost savings (customer level)

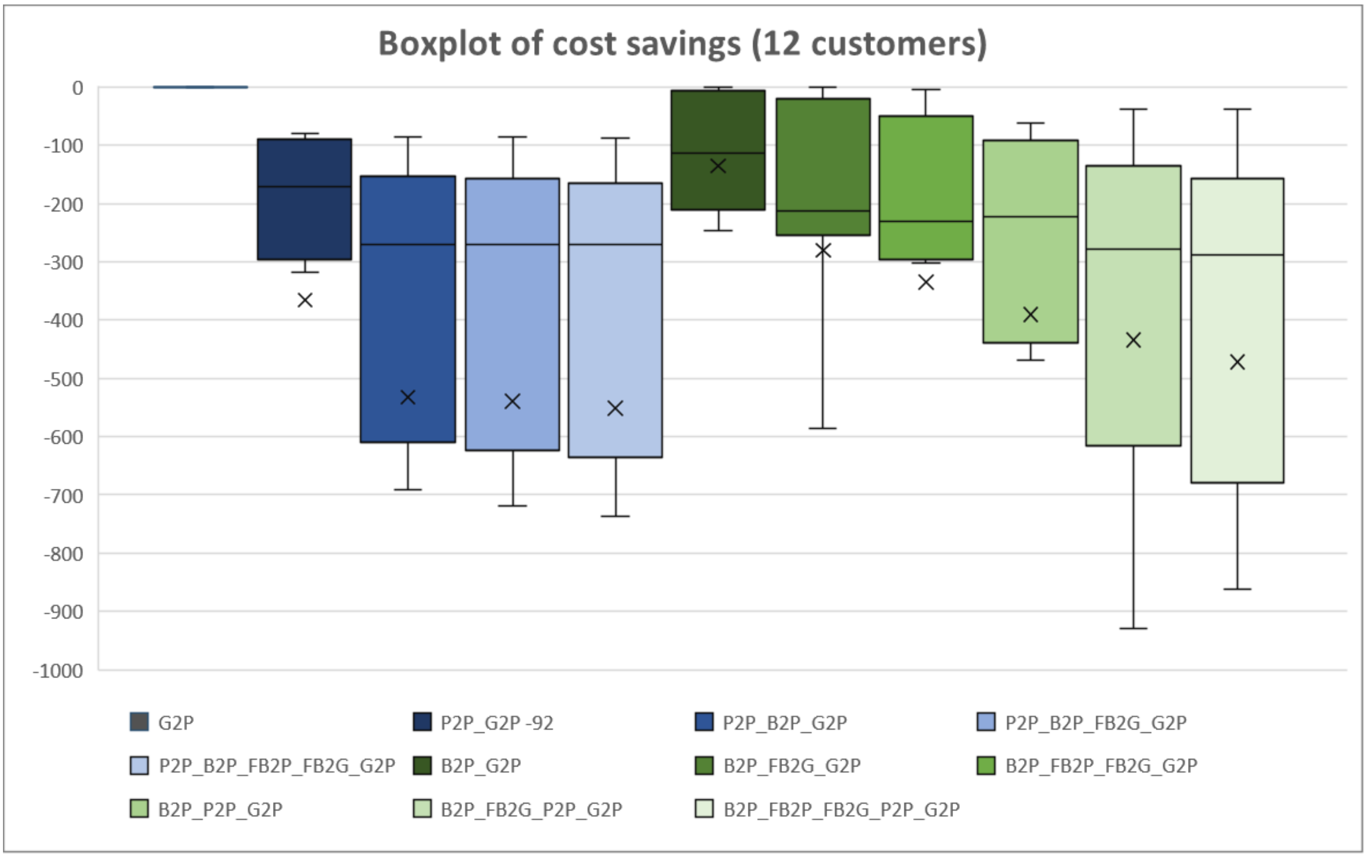


Figure 17: Comparison of total cost savings of the pilot customers - shown as boxplot, without outliers (2 commercial customers with up to 2.000 €, depending on the scenario)

Based on the calculated total costs (Figure 16), Figure 17 shows the potential cost savings [€] for the community customers and for each simulation scenario.

Similar to the previous figure, the two commercial customers (with savings up to 2.000 € each) are not shown due to readability. The average cost savings per customer vary between 135 € (B2G_G2P) and 551 € (P2P_B2P_FB2P_FB2G_G2P) per customer and per year – depending on the scenario.

7 Field Test

7.1 Community

The location of the field trial was chosen based on the problems in the local low voltage grid and the amount and density of the prosumers with PV-installations. Thus, municipality of Heimschuh in western Styria was selected which is supplied by 5 transformer stations 20/0,4-kV. The station Heimschuh II with its underlying low voltage grid has the highest penetration of PV installations with 23 PV installations as of 01/2020 with a total capacity of 150 kWp. The total consumption of the customers is 1 GWh electricity annually.

Due to a very high penetration of renewables (photovoltaic generation) and high loads, the DSO was forced to either reinforce the grid, which would result in high investment costs, or to resort to smart grids solutions such as a grid supporting storage system. Thus, the latter approach was taken in the project Blockchain Grid where the storage is used for grid support in times of high PV-generation and a dynamic free grid capacity algorithm has been implemented to allow customers to consume more electricity with higher power when this possible from the grid perspective.

7.2 Customers

From the 23 prosumers with a generator only 11 so called “self-consumers" were eligible for the project. Other customers are selling 100 % of the produced electricity over a feed-in tariff and do not have any interest in using a storage system. The installed PV capacity of the 11 customers is 100 kWp and all the customers signed a cooperation agreement to take part in the project. The 100 kW/100 kWh battery storage system was installed in the mentioned LV grid already in the previous project LEAFS and has been integrated into the new blockchain-based concept. There was already one customer in the grid with an electric car with further customers showing interest to buy one. This location was therefore also well suitable for the tests with the automatic allocation of free grid capacity.

7.3 Setup / Realization Heimschuh incl. CMDA

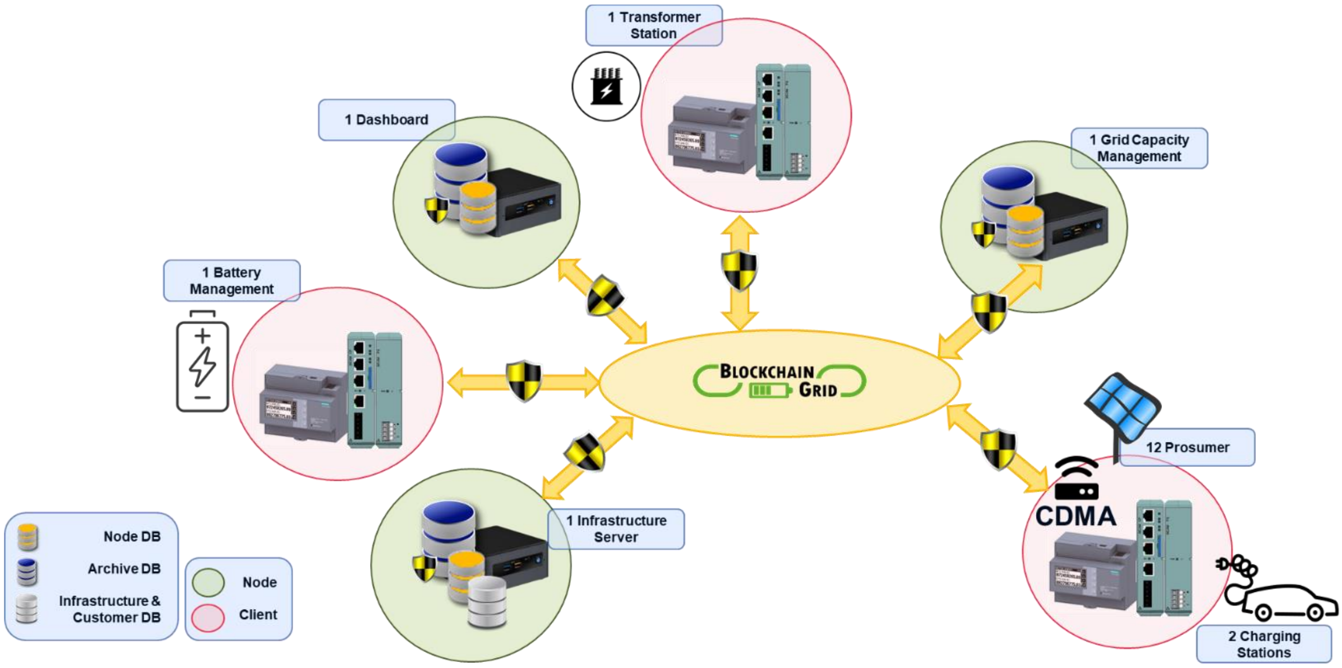


Figure 18: Structure of the Setup / Realization in Heimschuh incl. CMDA

In the Figure 18 the setup in our field test in Heimschuh is shown. We have used Intel® NUC – Mini-PC as sealer, SIEMENS SICAM CP-8050 with PAC2200 as light clients and CDMA Modems for the communication to the Prosumer. Our overall configuration consists:

- 1x Infrastructure Server (NUC)
- 1x Dashboard (NUC)
- 1x Grid Capacity Management (NUC)
- 1x Battery Management (CP-8050, PAC2200)
- 1x Transformer Station (CP-8050, PAC2200)
- 12x Prosumer (CP-8050, PAC2200, CDMA Modem)
- 2x Charging Station (CP-8050, PAC2200, CDMA Modem)

The configuration and setup data are defined in the infrastructure server, and the devices can get all data and firmware they need via a simple web server (HTTPS). This server is also used the initiate the Blockchain and restart the chain on a monthly base (accounting period). We are using only a separate dashboard within the system instead of gateways due to security reasons. With additional security topics it is possible to realize also the gateways regarding the concept. We have used a separate sealer as a server for the grid capacity management, which is outsourced from the smart contract. For the transformer station and the battery management we have the same clients as the prosumer.

7.4 Dashboard/User Interface

Due to the basic structure of the blockchain technology, the stored information (e.g., invoices) can be made available to the participants of the REC at any time in a comprehensible and transparent manner. This creates a high level of acceptance for the technology and trust among the participants. Access to the data of the participants in the REC according to the defined access rights is via web servers or gateways operated by individual nodes.

To access the data in the Blockchain, each participant receives an access identifier (username and password) which is linked to the customer data by the infrastructure server. Each sealer node and full node provides a way to login with the customer access ID to obtain data according to the respective access rights (gateway in Figure 8). In order to strengthen the relationship of trust between the participants and the nodes, the participant can determine which nodes he wants to connect to (see Screenshot in Figure 19). As the full nodes validate all transactions and smart contracts within the Blockchain independently the participant could check, if desired, whether every node shows the same data. The credentials are validated via the infrastructure server, which notifies the respective node of the Blockchain ID, the role and access rights of the participant asking for data access. For example, a pro-/consumer has only access to his own data (like sold energy, measured load data, ...) whereas the community representative can access aggregated data of the overall community operation (e.g., sold energy of the community, share of individual participants) to ensure optimal conditions for the community.

Furthermore, the gateway software should offer the possibility to receive settings from customers and to pass them on to the smart contracts that control the processes of trading in the blockchain, e.g., whether the participant wants to save his surpluses in the central BESS as a priority or if the focus will be on energy trading within the community.

The gateway software developed to meet the developed concept consists of a web server that allows access to certain data (e.g. only those of the respective user) via the aforementioned user password query (green arrows "Gateway" in Figure 8), the Node DB (yellow database structure in Figure 8) and a Blockchain connector (yellow arrow in Figure 8), which allows access to the data in the Blockchain. The access rights are managed by the infrastructure server and made available to the individual "nodes" (green circles in Figure 8). The gateway can connect to any node to allow the user to check that each of the nodes is holding the same data. As mentioned before in the field test only one node provided the functionality of the gateway software, due to security reasons. But a deployment of the gateway software to other present nodes was every time possible.

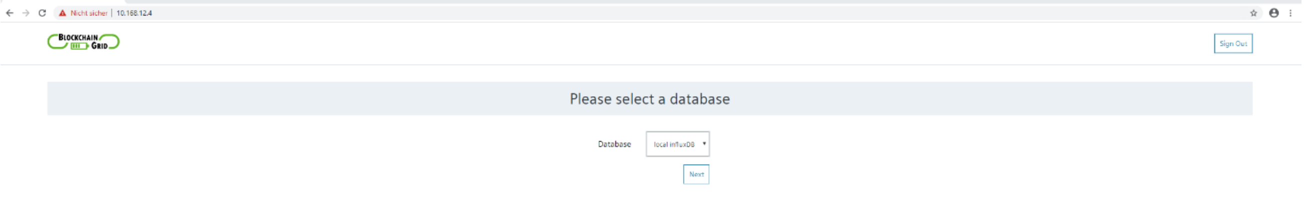


Figure 19: User selects the node database, he wants to connect to

In addition to the individual participants roles of the REC, an additional administrator role was defined, which, with the consent of all REC participants, has access to all REC data. This role was also created regarding the test environment in the field test in order to quickly receive the data from the Blockchain and to monitor the operation of the REC.

After entering the gateway software with the administrator role, it is now possible to select and display the data of different REC participants. This is the measurement and process data that the clients (red circles in Figure 8) have stored in the blockchain. E.g., the "toNet" variable represents the energy or power supplied to the distribution network (average power value over the measurement period).

In Figure 20 and Figure 21, this measured variable was shown for two different users via the gateway software.

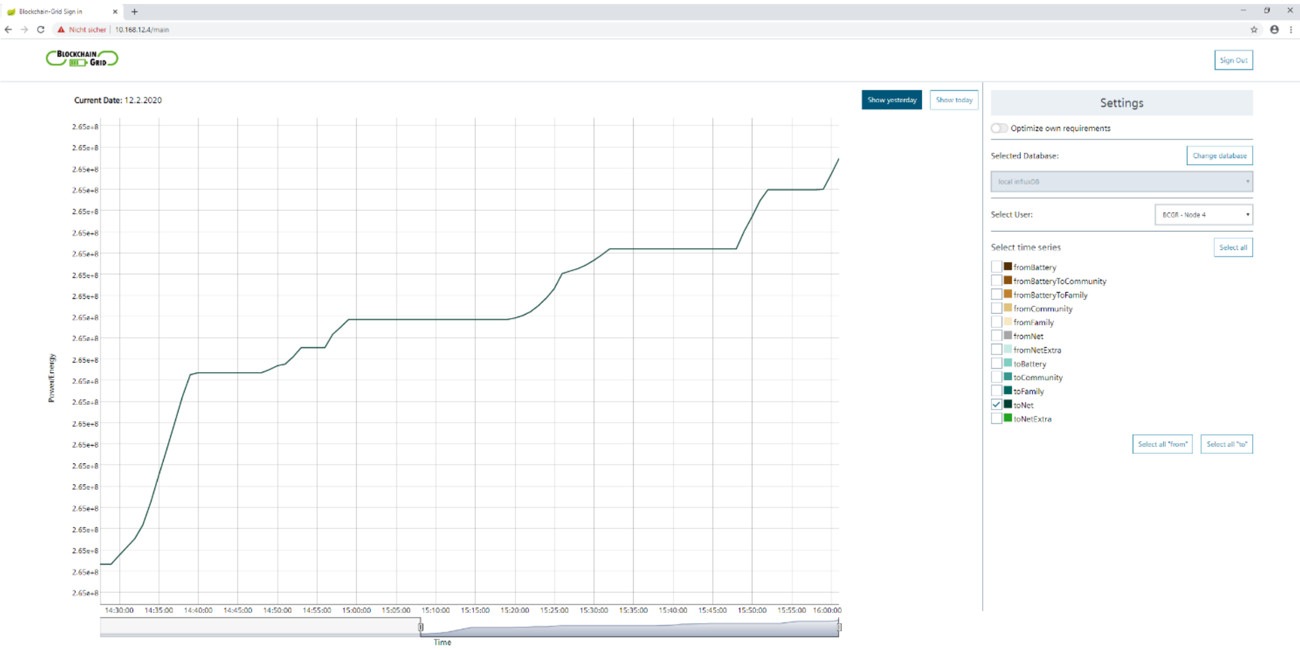


Figure 20: "toNet" Data of the EC-user "BCGR – Node 4"

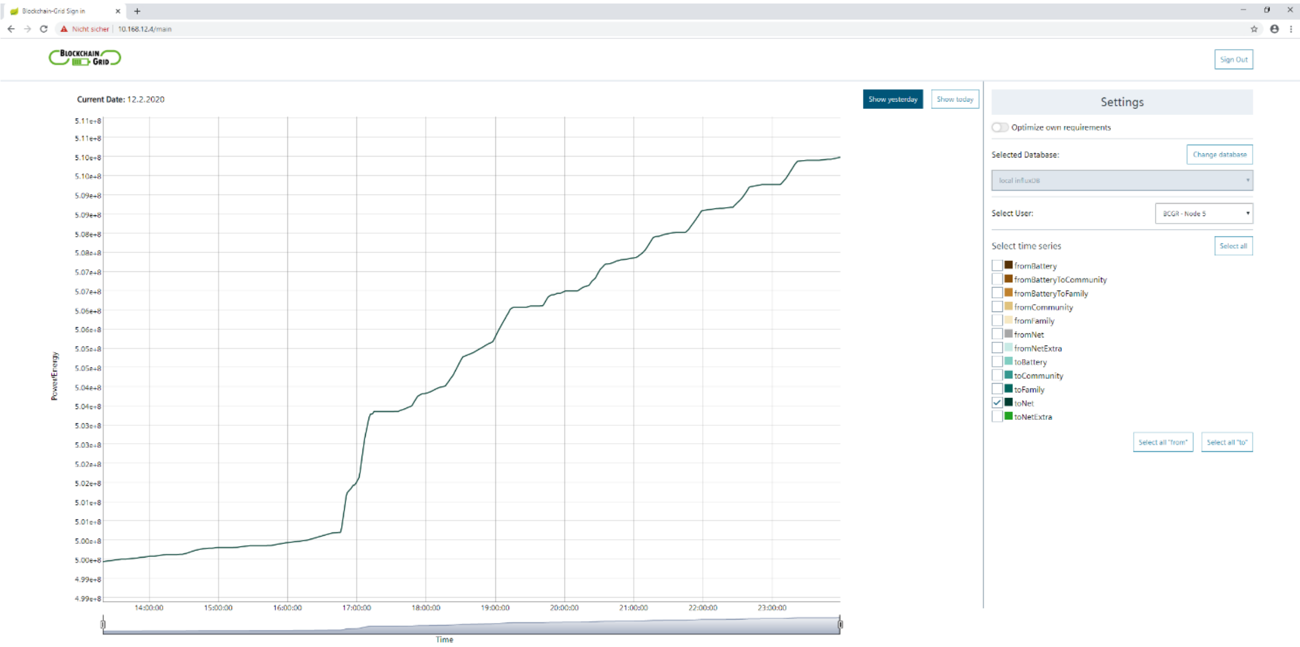


Figure 21: "toNet" Data of the EC-user "BCGR – Node 5“

Figure 22 and Figure 23 show the data point “FromNet as another example. This data represents the energy or power of the respective REC participants drawn from the distribution network. Figure 22 and Figure 23 show this access to the data for two of the EEG participants.

Figure 22: "fromNet" Data of the EC-user "BCGR – Node 4“

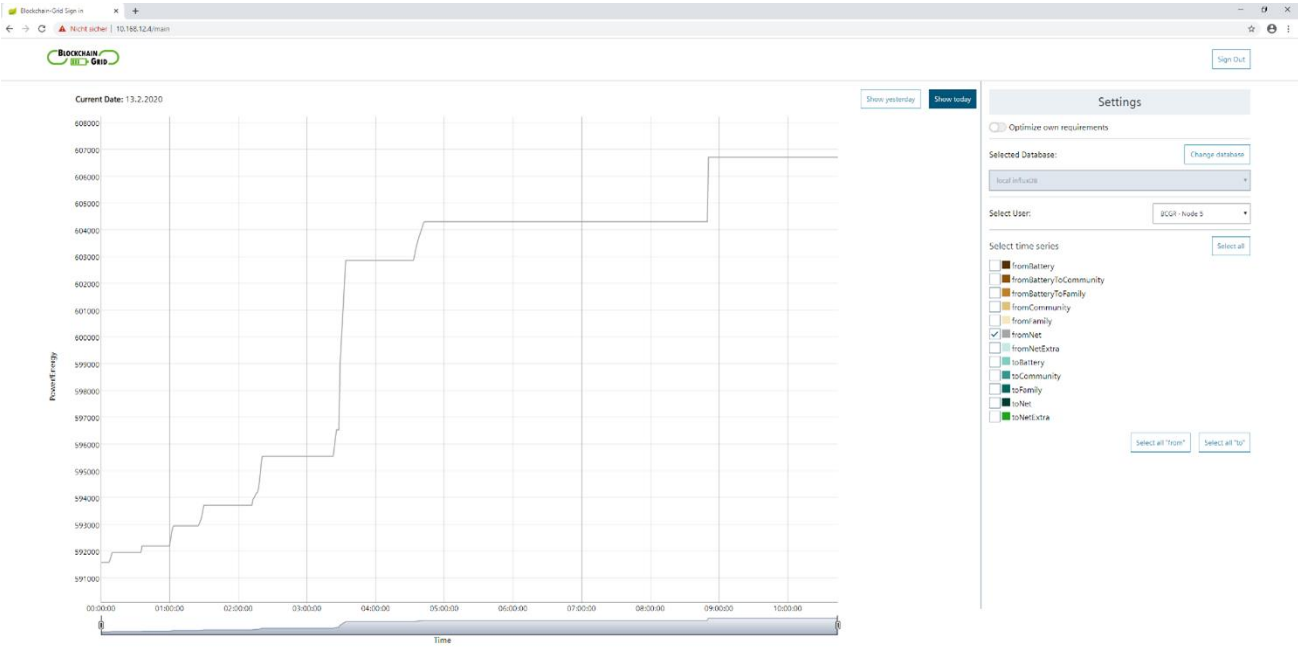


Figure 23: "fromNet" Data of the EC-user "BCGR – Node 5“

7.5 Results

7.5.1 Market Smart Contract

Figure 24 shows the measured power profiles of the twelve pilot customers within the demo region. The profiles illustrate the aggregated power (generation and consumption) within 24 hours with a resolution of one minute. Based on the course of the profiles, it can be seen that most of the customer has a high local generation about noon. Furthermore, the profiles show a high variety of the maximum (demand) power of the measures customers – ranging from approximately 40 kW (Customer #1) to less than 1 kW (Customer #12), as well as partly very high generation (more than 6 kW for Customer #11).

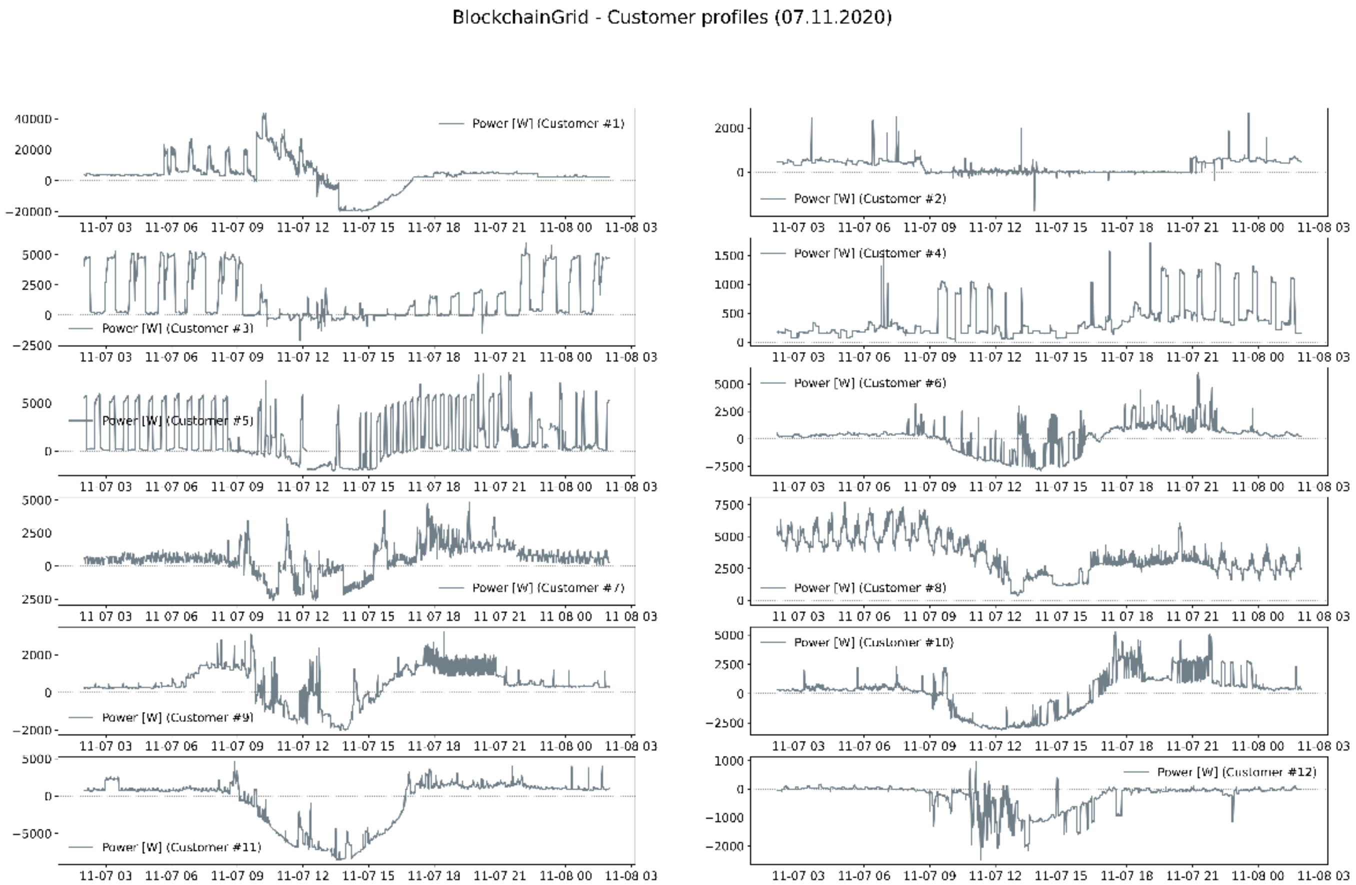


Figure 24: Aggregated power profiles of pilot customers

Figure 25 gives an overview about all energy transactions within the community with the twelve pilot customers by using their aggregated customers (self-consumption is already covered). Within the community, approximately 240 kWh are covered by the public grid ("*fromGrid*"), approximately 20 kWh are fed into the grid ("*toGrid*"). In total, 68 kWh are stored within the community battery storage ("*toBattery*"), 36 kWh are re-used by the customers ("*fromBattery*"), whereas 32 kWh are sold to other customers ("*toComfromBat*"). Within the community, approximately 36 kWh are sold directly to other community customers ("*toCommunity*"). In total, 68 kWh are bought within the community ("*fromCommunity*") – composed of direct transaction ("*toCommunity*") and indirect via the battery ("*toComfromBat*"). Additionally, it can be seen that there are transaction between customers within one family community (LFC): 580 Wh are used within the family ("*fromFamily*"), composed of direct family transactions ("*toFamily*") and indirect via the battery ("*toFamfromBat*").

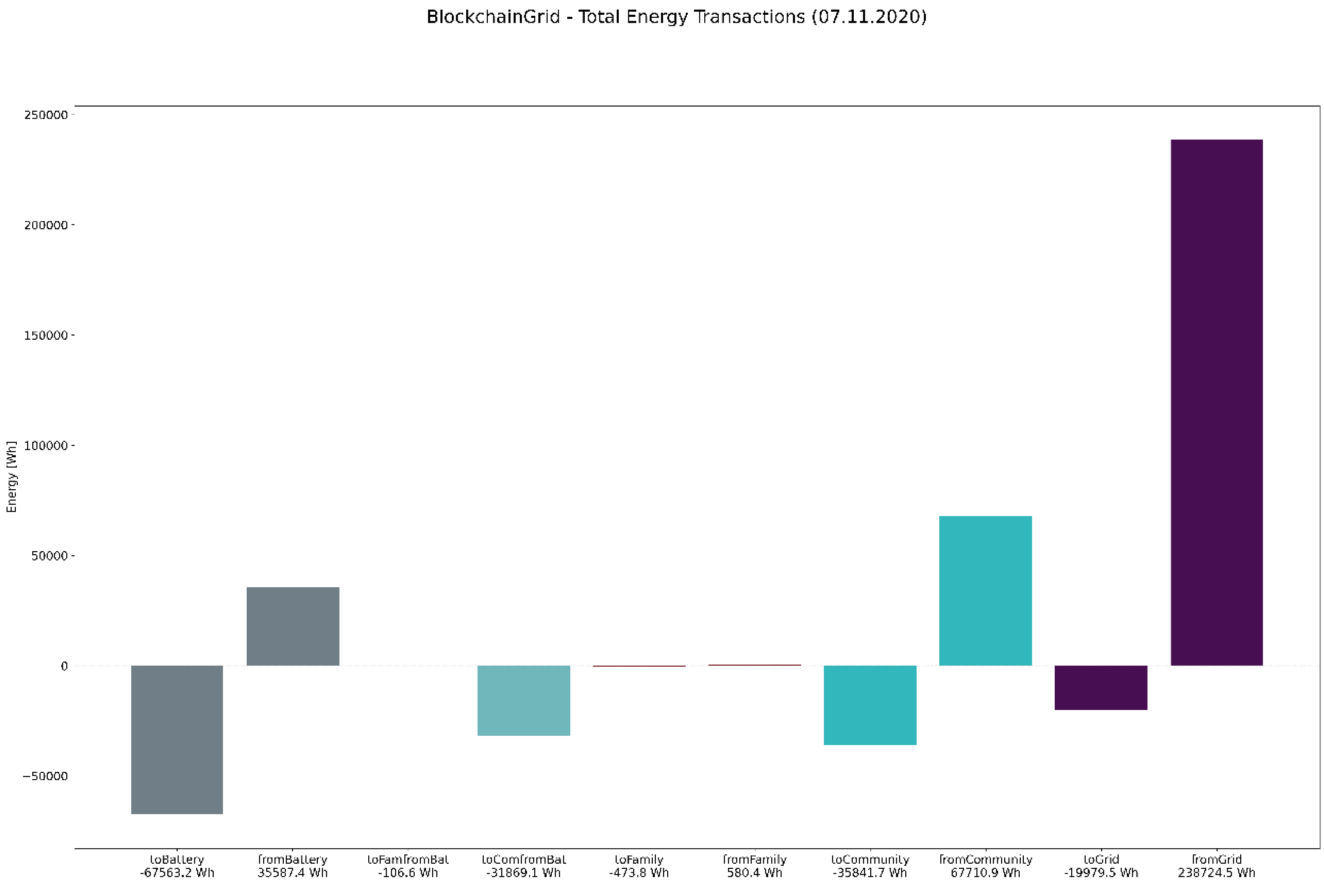


Figure 25: Energy transactions of the entire community in November 2020.

Figure 26 illustrates the calculated energy transactions (illustrated as power in W in a resolution of 1 minute) of one of the pilot customers of a selected day (with sunny weather and high local generation) in November 2020. The top diagram of the figure shows the energy transactions as time series – above the x-axis (positive range) shows demand, below the x-axis (negative range) shows surplus. It can be seen that at night (before 09:00 and after 20:00), the demand is covered by energy from the public grid, whereas between 09:00 and 20:00 the generated energy is used by the customer, provided to other community customers, and stored in the battery. On the other hand, energy from the battery is re-used and partly bought from other community customers. The lower part of the diagram shows the aggregated amount of energy (in Wh) by each category.

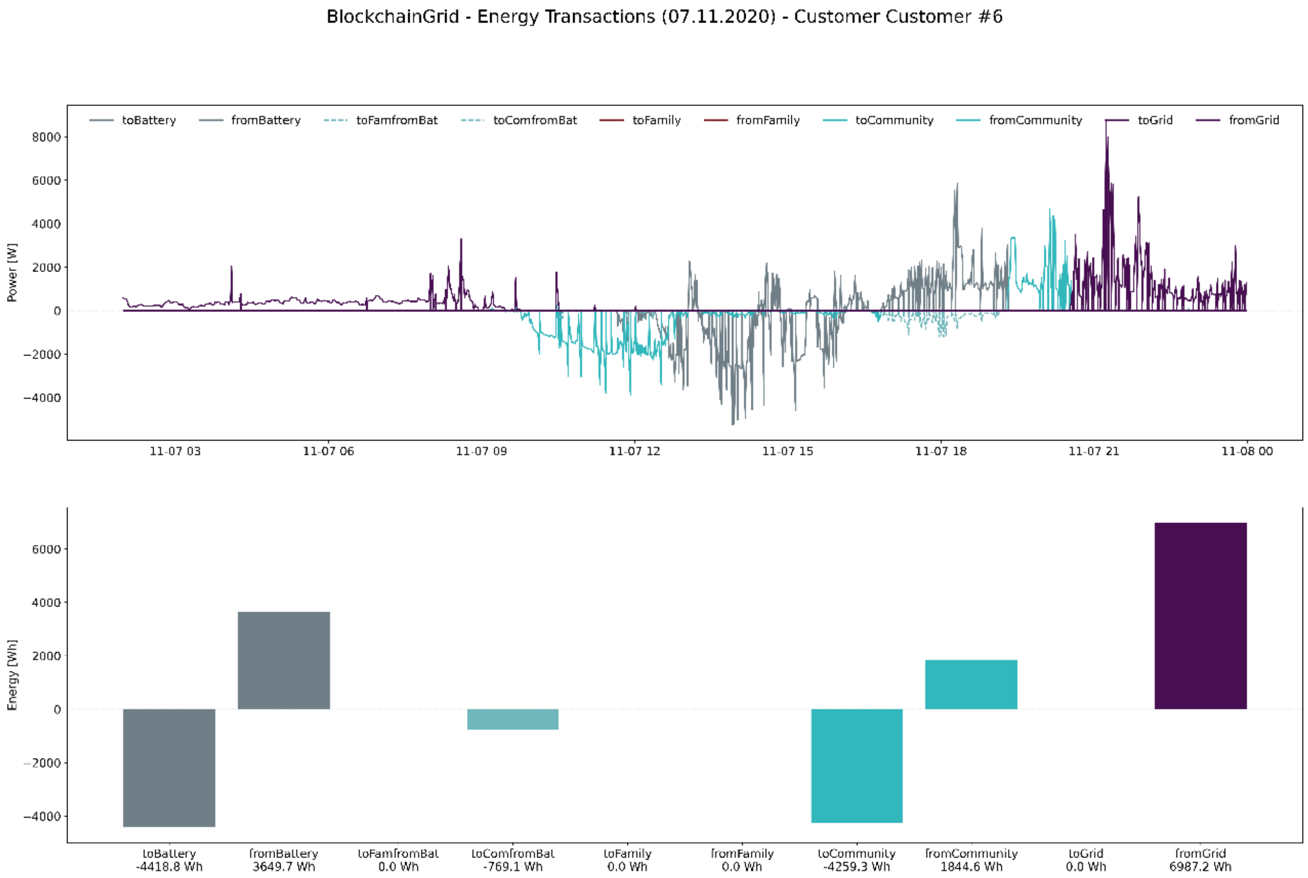


Figure 26: Energy transactions of one pilot customer in November 2020.

The following energy transactions are calculated for the selected customer within 24 hours:

- ~4.400 Wh of the generated energy is stored into the battery.
- ~3.700 Wh of the stored energy is from the battery by the customer.
- The remaining ~700 Wh are sold to other community customers.
- Additional ~4.300 Wh is sold within the community.
- ~1.900 Wh are bought from other customers.
- Finally, 7.000 Wh are served from the public grid.
- For this customer, no family condition is considered.

7.5.2 Grid Capacity Management

GCM is currently deployed in the field in Heimschuh at the community battery container. Measurements and GCM setpoints are logged and the results are presented here.

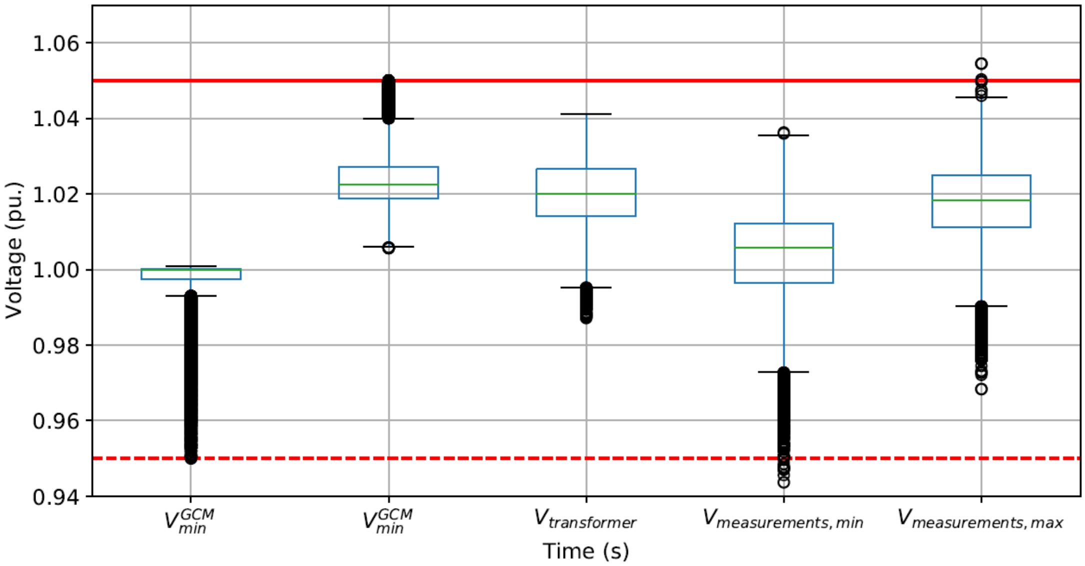


Figure 27: Voltage measurements from transformer, after GCM applications, and measurements from Blockchain Grid customers.

In Figure 27, V_{min}^{GCM} and V_{max}^{GCM} are the voltages generated after applying the limits generated by the GCM. $V_{transformer}$ are the voltages measured at the transformer. $V_{measurements,min}$ and $V_{measurements,max}$ are the voltage measurements from various Blockchain Grid customers.

Under and over voltage events are observed in $V_{measurements,min}$ and $V_{measurements,max}$, respectively. However, it can be observed that after applying the GCM limits, the voltage violations are completely eliminated. Therefore, the GCM can preemptively provide market settlement even before the energy accounting is executed. This enables the energy accounting system to operate safely.

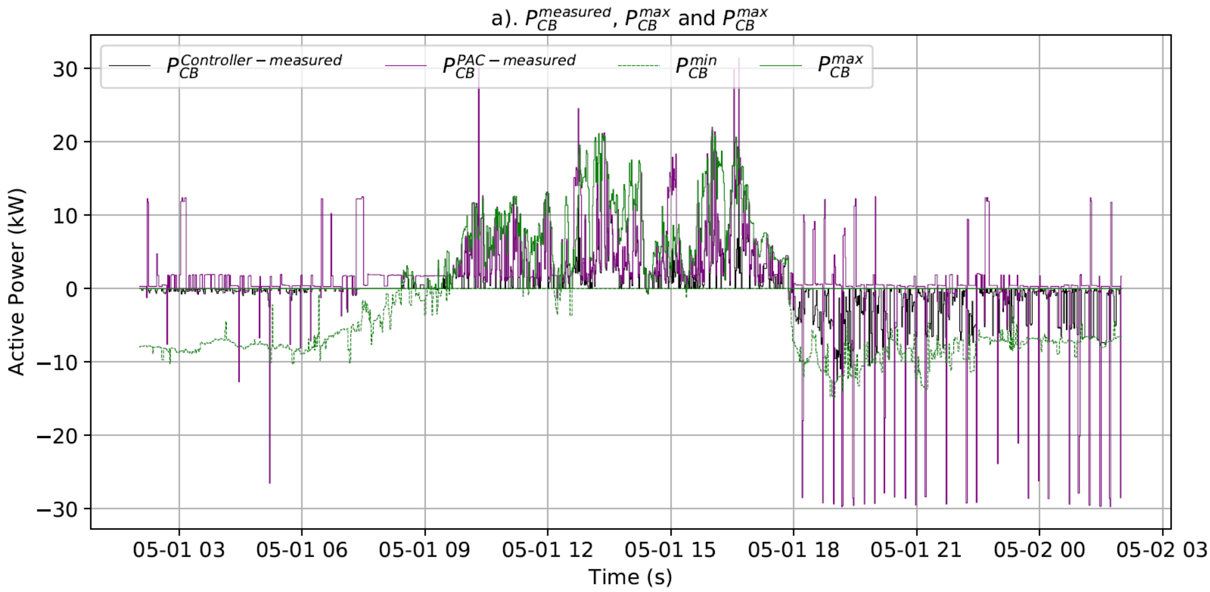


Figure 28: GCM limits applied to the community battery.

The setpoint generated from the GCM are transmitted to the community battery controllers. It can be observed in Figure 28, that the battery controller ($P_{CB}^{Controller-measurement}$) is perfectly within the limits from GCM (P_{CB}^{min}, P_{CB}^{min}). $P_{CB}^{PAC-measurement}$ is the active power measurement at community battery container. It can be observed that there are other loads in the container like industrial PCs, lighting and ventilations system.

The market smart contract uses these limits to generate the actual battery charging or discharging setpoint based on the accounting priorities and needs. As long as $P_{CB}^{Controller-measurement}$ is within (P_{CB}^{min}, P_{CB}^{min}) limits, no voltage violations are observed in Figure 27.

8 Conclusion and recommendations

8.1 General Results

According to the simulation results, the customers can potentially save up to 500 EUR/year from P2P trading and the use of the community storage system once the Clean Energy Package has been implemented in Austria. The potential savings strongly depend on the relation between total yearly generation and consumption of community participants and their respective generation and load profiles. This load/generation balance also strongly determines the need of a storage system in the community setup.

In terms of grid capacity, 50% more renewables can be connected to the grid due to the use of the grid capacity management developed in the project. In reality, 4 additional PV installations with total power of 40 kWp were connected to the grid in Heimschuh due to the project implementations. This solution makes the local energy community of Heimschuh grid friendly and can potentially lower the total costs of grid expansion in case of a mass roll-out in Austria.

Due to the development and implementation of the capacity sharing use-case, blockchain grid customers could load their e-cars not only with the standard 11 kW but with up to 22 kW according to the momentarily available grid capacity. This greatly speeds up the charging time of the e-cars and is a good alternative to the very cost intensive classical grid expansion.

8.2 Architecture design

Based on the results of the KPI evaluation, we would recommend a combination of decentralized IoT and a Blockchain system. High performance, small latency and a big amount of data are necessary to control the dynamically smart grid in the field. IoT candle handle these requirements on a tiny embedded system, also for the algorithm. Smart contracts are normally designed for smaller applications. We would recommend a decentralized system to separate the smart grids from each other. This is much better for the resiliency and availability then centralized IoT systems.

Functionality in the decentralized IoT:

- Acquisition of the measurement data
- Local (on-site) Monitoring and Controlling (sensors and actors)
- Control Algorithm
- Data Concentration to 15min values

The Blockchain system is used to get more transparency and a trusted documentation. A private layer 2 Blockchain can be used for P2P energy trading based on 15 min values and as a trusted documentation. This will be handled in a smart contract and can be verified with a public layer 1 blockchain.

Functionality in Blockchain System:

- P2P Trading based on 15min values
- Trusted documentation for accounting

8.3 Communication/CDMA

There is a big amount of data for synchronizing the Blockchain, also on the light client. Therefore, a stable communication solution with higher bandwidth is recommended if you are using the Blockchain for the embedded sensors and actors. We have also recognized a problem with the stability and the coverage of the CDMA network if you are using the communication network for a fast control algorithm, because the data from all sensors are needed in an interval of every minute. It’s much better in our optimized solution where the IoT is used for cyclic measurement data from the field. The 15min meter data can be used for the P2P energy trading. So, there is a better failure tolerance for the communication in applications like this. It should be mentioned that for the control of controllable devices (e.g. storage system and charging stations) a higher data transfer resolution (e.g. 1 Minute) is needed that for the billing purposes (15 Minutes time step).

8.4 Legal and regulatory aspects

Based on the regulatory analysis, the following actions would help to enable future implementation of Blockchain-based energy communities:

- Grid-supportive behavior of the community could be accomplished through explicit consumer and/or community contracts with the DSO. This would allow the DSO to manage load within the community according to the grid status and promote remuneration schemes for grid-supportive generation and consumption. Such grid supportive functions of LECs (in frame of flexibility markets for DSOs) would potentially lower the costs for grid expansion to accommodate renewables in the next decade.
- A new legal framework is needed for community storage systems including new tariff structure (the double grid tariffs for the use of a community storage system should be reconsidered). This new framework should allow for economically efficient multi-use of storage technologies, which makes sense due to high up-front costs when putting up new systems.
- It is recommended to have simplified authorization procedures for energy communities to qualify as electricity traders/electricity suppliers to support market integration and provide communities with more flexibility.
- Studies need to be conducted in order to depict different possibilities and costs/benefits concerning balancing responsibility, not only within but also beyond an energy community to ensure that those consumers that are not part of the community are not unfairly disadvantaged.
- It is recommended to link grid tariff and levy reductions based on the grid-supportive behavior of an energy community.
- In order to safeguard all consumer rights and liability in the event of faulty operation, a contract between all members of or the representative of the energy community with the operator of the Blockchain platform must be concluded.
- The operation of electric vehicle charging infrastructure, so far unaddressed in the EAG draft, should also be explicitly enabled for renewable energy communities. This includes new tariff model for charging with powers higher than contractual power in times where this is possible from the grid perspective.
- The funding call for regulatory sandboxes, following the enactment of the EAG package, shall identify guiding tariff structures for energy communities.

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10 Kontaktdaten

ProjektleiterIn

Institut/Unternehmen

Kontaktadresse (Adresse, Tel/Fax, e-mail; Webpage des Instituts/Unternehmen; Webpage des gegenständlichen Projekts, falls vorhanden)

Auflistung der weiteren Projekt- bzw. KooperationspartnerInnen Name / Institut oder Unternehmen