A Novel Architecture for a Peer-to-Peer Energy Market derived from a context specific Evaluation of Blockchain Technology - BC4P Report

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ABSTRACT

According to the blockchain technology Gartner Hype Cycle, decentralized exchanges can be seen as one of the innovation trigger technologies with high expectations. Decentralized Peer-to-Peer (P2P) market approaches nicely fit to an emerging prosumer model in energy markets and grids. This paper provides a comprehensive analysis on blockchain technology and concepts to facilitate P2P energy-trading markets. Based on this, a novel architecture for a future P2P energy market is introduced.

KEYWORDS

blockchain, smart grid, distributed ledger, peer-to-peer, P2P

ACRONYMS

DAG	Directed Acyclic Graph
DLT	Distributed Ledger Technology
DNS	Domain Name System
DSO	Distribution System Operator
EP	Electricity Provider
FCR	Frequency Containment Reserve
OTC	Over-The-Counter
P2P	Peer-to-Peer
PBFT	Practical Byzantine Fault Tolerance
PKI	Public Key Infrastructure
PoA	Proof-of-Authority
PoS	Proof-of-Stake
PoW	Proof-of-Work
TLS	Transport Layer Security
TPM	Trusted Platform Module
TSO	Transmission System Operator
V2G	Vehicle-to-Grid
aFRR	automatic Frequency Restoration Reserve
mFRR	manual Frequency Restoration Reserve

1 INTRODUCTION

The emergence of renewable power supply systems e.g. photovoltaic systems or wind energy converters lead to particular challenges in the energy market. Separate roles such as generator and consumer must be transformed into a prosumer role, leading to the particular problem of rigorously increasing the number of electricity generating units or market participants. As a consequence, the classical hierarchically structured unidirectional power flow has changed to a significant more complex system. Unfortunately, the current regulatory framework in Europe does not represent the actual power flow sufficiently and prevents smaller participants from joining the market [41]. Hence, the question arises whether more distributed market approaches could address this issue.

Distribution and transport grid capabilities are often separated from the energy trading - in Germany by law.

While classical large scale producers and consumers can respond to the market by adapting their production or consumption, the flexibility of small prosumers is so far neither claimed nor actively used. Small prosumers do not directly participate at the market, so there is a lack of appropriate market based incentives. Several approaches [20] [37] [24] aim to solve this problem based on a peer-to-pool design. However, they are not adding any incentives to take the grid capabilities or flexibility into account. The concept for the wholesale market does not change. Recently, a strategy has been proposed that embeds peer-to-peer markets into the existing market construct, e.g. in [44].

The blockchain technology and Distributed Ledger Technology (DLT) is often mentioned to solve those problems, especially the possibility to trade P2P in a market consisting of many entities. The core concept is the distributed consensus mechanism which does not need a central coordinator or any kind of trusted authority for price settlements. While the blockchain technology is widely used in digital cryptocurrencies, its application in other domains is less significant. One of the major difficulty of using this technology is to combine the real-world energy assets with digital assets of a blockchain. This paper evaluates the applicability of the features provided by the blockchain technology for a P2P energy market. While the results provide a better understanding of the problem domain itself, the authors also provide a counterproposal for a future energy market design.

The paper is structured as follows: section 4 provides a brief overview of energy markets, extended by a description of the particular challenges. The evaluation of using blockchain and P2P technology for a modern market design is revisited in section 5. Different existing market designs are presented and compared in

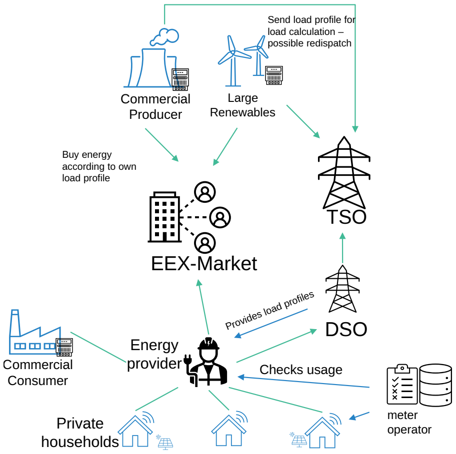

Figure 1: Current electricity market in Germany: Households are aggregated and get a fixed price, the energy provider uses load profiles provided by the DSO

section 6. Finally, a novel concept to solve the challenges of current energy markets is provided in section 7. Here, the market design aims to match the hierarchical grid structure. Finally, the results are then summarized in section 8.

2 ENERGY MARKET IN GERMANY

The energy market in Germany has many participants, outlined in figure 1. Large power plants, renewable energy sources (RES) and energy providers trade the energy generation and consumption at the European Energy Exchange (EEX) market, where the price clearing is currently implemented as merit order for the Day-Ahead-Market. A grid fee is implemented to remunerate the use of the transmission grid. The distribution service operators (DSO) manage the lower voltage networks and generate the forecast lines for consumers which are not part of the "regulierte Leistungsmessung". Those forecasts are scaled and used by energy providers to calculate the tariffs of customers. The demand calculation for all customers of a electricity provider is also used to buy the needed energy from the EEX market.

Every year the metering point operator (Messstellenbetreiber) reads the analog meters of all households to check the yearly consumption. The sum of all demands must equal the bought energy for every quarter hour in the area of a balancing group (Bilanzkreis), which must be controlled by every balancing group manager.

2.1 Grid overview

A special characteristic is that the country is divided into four regions which are operated by different TSOs, namely TenneT, Amprion, 50Hertz and TransnetBW. The outlines of the areas are shown in figure 2. The subdivision into four areas allows to use a basic classification of different zonal areas with different prices. In the future the separated prices will be removed and the same grid fees will be applied in the whole country.

Figure 2: Regions of the four TSOs operating in Germany; Source: Francis McLloyd, CC BY-SA 3.0

3 REGULATORY FRAMEWORK

In this section, important regulatory laws for German electricity providers are described

§14a Stromnetzentgeltverordnung. Starting in 2023, the grid fees should be consistent in the whole country [2]. With this regulatory change the implementation of dynamic grid fees will become more difficult in the future. The need for grid-serving behavior of prosumers must be applied differently or with another fee as the grid fees won't become dynamic in the future. A possible solution could be that the transmission system operator (TSO) will publish a load curve which is respected by the prosumers without a financial benefit.

Eichrecht. The german Eichrecht is in law since the 01.04.2019 and ensures that the customer has the possibility to control the calibrated meter values of a charging station [3]. This is a real world use case of electricity meters which transfer cryptographically secured meter values. The same framework can be adapted for the implementation of a smartmeter infrastructure.

Renewable Energy Sources Act. The Erneuerbare-Energien-Gesetz (EEG) regulates the prioritized feed-in behavior of renewable energy sources. A fixed feed-in tariff for renewables has been implemented to enable the sustainable development of energy supply, in particular in the interest of climate and environmental protection [1]. In the future the subsidies of renewables will diminish as the profitability of renewables increases.

Smartmeters. Currently, only large generation units with more than 100MW per year need the so-called "regulierte Leistungsmessung" (regulated power monitoring) [12]. Those have an electricity meter which communicates the energy usage every 15 minutes to the TSO.

Additionally, starting in 2021 new photovoltaic plants with a capability of more than 7 kW must implement a smartmeter for a continuous energy monitoring [17].

4 ENERGY GRIDS, MARKETS AND ITS CHALLENGES

From a generalizing perspective, an energy system consists of a distribution grid, a market, and its participants, where a participant can produce energy (producer), consume (consumer) or do both (prosumer).

4.1 Grid Operation

Due to its physical appearance of its assets, grids are monopolistic and operated by a single entity, which are also called natural monopolies. In abstract terms, the task of the power grid is to connect the individual participant with each other in order to enable the flow of electricity. Here, various problems have to be addressed:

Power Limits. A key element of the grid is the power it can handle which is restricted by its physical characteristics. Currently, this limitation is insufficiently addressed in most markets, and is respected after market clearing took place. For example, in Germany, a re-dispatch takes place after market clearing to avoid congestion of the network. Each line l has a maximum power $p_{l_{max}}$ it can transfer at a given time-slot t:

$$\forall t \in T : p_{lt} < p_{l_{max}}$$

Failure Safety. Another key element is the failure safety, it is possible that a power line fails and therefore participants are not reachable. The Distribution System Operators (DSOs) duty is to ensure, that the effect of such an outage does not propagate through the network. Therefore, N-1 stability comes into place, stating that the grid should be capable to handle the outage of any single line without cascading effects into more failures [11].

Discrete Market Interval. One major challenge for the grid is the discrepancy between the time intervals of market, which acts with discrete time intervals and the physical power flow which is a continuous measurement. Expressed differently the market is handling energy (Wh) while the physical grid handles power (W). Operating the grid and managing that the sum of the generation equals the total consumption at any time is crucial to the stability of the whole energy system.

For every time-slot t and for every market participant i who trades at the market (N) the sum of all traded energy a must be net-zero:

$$\forall t \in T : \sum_{i=1}^{N} a_{it} = A_t = 0$$

Thereby a is positive for sold energy (production) and negative for bought energy (consumption) at the market. This must also be true for the physical energy flow e. In this case the energy flow is continuous without fixed intervals:

$$\forall t \in T : \int^{t} \sum_{i=1}^{N} e_{is}\, ds = E_t = 0$$

Finally, the traded amount A_t must match the physical energy flow E_t for every time-slot t:

$$\forall t \in T : A_t = E_t$$

Demand and Generation Forecasting. To ensure a stable energy system each participant forecasts the amount of demanded or generated energy to buy/sell at the market. As the energy forecast has its uncertainty, the traded energy of a unit i for a time interval t does not always match the respective energy flow:

$$a_i t = e_i t + \Delta e_i t$$

The deviation $\Delta e_i t$ must be balanced out by balancing providers to secure the grid stability. The process to find the best schedule for the next time slot is getting less stable with the emerge of renewable energy generation, as those depend a lot more on the current weather situation [19]. While the instability of the generation is quite new, the consumption has never been completely stable as consumer behavior is not accurately predictable.

This effect evens out when multiple consumers are aggregated by an electricity provider. But in P2P market designs, the uncertainty for a single household can be very high, ending in high costs for prosumers with a bad forecast, as they have to pay fees for $\Delta e_i t$ for every time-slot.

To reduce the risk for a single prosumer, aggregated small prosumer groups which trade together at the market are one possible solution. Another approach would be to use batteries as energy cache to reduce $\Delta e_i t$.

Small market participants cannot manually enter or generate their forecast on a daily basis, without having a bad user experience for most people who aren't interested in the energy prices. Therefore, the forecasting has to be done automatically with a forecasting system, which constantly predicts the best strategy for $a_i t$ based on historic data and the available generation capabilities.

Balancing Energy. It must be ensured that sufficient balancing energy is always available to compensate for major grid fluctuations, without damaging the network or causing outages. This can be managed centrally or with a dedicated auction at a balancing market. Currently, this challenge is addressed in Europe by providing balancing energy at a seperate market layer, while the amount of balancing energy is calculated by the grid operators.

4.2 Market Evolution

Markets are responsible for coordinating supply and demand with price information. During its 140 years of existence, power grids and corresponding markets lived through different phases. Historically the energy grid and market was centrally organized with a top-down approach.

Monopoly. Energy was generated by larger scale power plants and purchased by all consumers from the energy distributor (phase 1, figure 3). In this scenario, a few entities control grid and production facilities. While this form of market has the lowest complexity, producers have a great influence on the consumers. Consumers are completely dependent on the grid operator and associated energy producers available at their location and have no option to switch to another producer.

To liberalize the energy market structures, the whole system and market changed from a centralized monopolistic approach to an open and more decentralized structure. This change is still an ongoing process.

Liberalized Market. In a liberalized market the market is divided in several roles and a regulator demands that one entity can control only one role. While this takes a lot of oversight and regulation it reduces the market power of each entity. The grid operator and energy producer are separated roles in a liberalized market, it is therefore possible to buy energy from any producer that is connected to the grid which incentives a competition between producers (phase 2, figure 3). Due to the complexity of the market new participants experience high entry barriers and hinders small producers to participate. In order to aggregate consumers, energy suppliers were established to purchase energy for many consumers on a wholesale market. This reduces the amount of participants at the market, yet also prohibits end users from trading produced energy directly on the wholesale market. Also due to this structure end users are decoupled from incentives resulting from short and midterm price fluctuations which would be a direct demand side management by market price as proposed in transactive energy concepts [22].

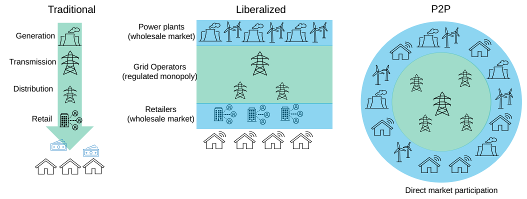

Figure 3: Market liberalization allowed to break up monopolies. In the regulated market small generation is not traded flexible. P2P enables direct market access for all participants

P2P market. One further step would be the establishment of a P2P market. The increase of decentralized renewable energy production pushes the need to integrate the flexibility of small individual participants into the electricity market. Trading directly at the wholesale market can increase the willingness of end-users to provide their flexibility. The emergence of battery storage and emerging Vehicle-to-Grid (V2G)-capabilities can also add currently unused flexibility for households to support the grid balancing. On the other hand, the current market is not designed for P2P trading or the integration of individual small participants [9]. Allowing all participants to directly trade energy without any aggregation like energy providers would probably result in scalability issues as the number of participants would increase greatly.

Recently, P2P markets were proposed to solve these challenges. Unfortunately, the definition of a P2P-market is quite vague. A unifying element of a all P2P market approaches is to allow all participants to take part in the market. Some concepts refer to the capability to trade directly and unregulated with every other market participant without the demand of a controlling third party. This raises the question on how market participants find each other and how they can ensure an adequate knowledge of the current market without being a possible victim to sybil attacks. Other P2P concepts propose two-tier markets that allow trading within a pool but otherwise keep the centralized regulatory framework [21]. Additionally, it is often unclear whether participants are involved in the provision of balancing energy or whether this is done centrally. Most concepts are not addressing the issue of balancing energy at all.

Concluding, a P2P market allows to use the flexibility of every single participant by setting an incentive through the price to consume energy grid-serving. Furthermore, trading between two individuals integrates small prosumers better into the market.

4.3 Challenges of the electricity market

The outlined requirements and challenges for a novel electricity market are summarized in this section.

A proposal for an energy market needs to cover the following features:

1. Creation of incentives for all participants to respect the grid's demand and limits (price signal and grid fees based on congestion)
2. Respect grid capabilities to reduce the redistribution after market clearing
3. Discrete tamper-proof measurements from every participant's electricity meter must be available
4. Participants should not be identifiable at the market to prevent discrimination
5. Balancing Energy must be provided in the market system to come up for the deviation between the physical flow and the traded volume.
6. Entry barriers should be low
7. Market needs to be scalable, so each prosumer can become separate participant

5 BLOCKCHAIN TECHNOLOGY

The use of blockchain technology is often seen as a revolutionary element for digital systems. The Merriam-Webster Dictionary defines the blockchain as "a digital database containing information (such as records of financial transactions) that can be simultaneously used and shared within a large decentralized, publicly accessible network" [25]. IBM defines blockchain as "a shared, immutable ledger that facilitates the process of recording transactions and tracking assets in a business network" [18]. A more technical definition can be found in the ISO standard 22739:2020 where it is defined as a "distributed ledger with confirmed blocks organized in an append-only, sequential chain using cryptographic links". Distributed ledgers are also defined here as a "ledger that is shared across a set of DLT nodes and synchronized between the DLT nodes using a consensus mechanism" [36].

All the above-mentioned definitions lack of explicitly referring to one of the major innovative parts of blockchain technology: its decentralized sequential consistent consensus. According to the FLP impossibility [14], there is no consensus protocol that is guaranteed to always terminate under all conditions, if at least one node may experience failure. DLT is often advertised as decentralized, efficient, censorship resistant, highly available, secure, anonymous and transparent[27]. It can be seen as a problem domain that is interfacing the FLP impossibility problem of asynchronous systems that lack of timeout values for its messages. While liveness cannot be guaranteed for sure, blockchain networks working with probabilistic consensus protocols like PoW or PoS are unlikely to be starved. We now further discuss the properties of DLT with respect to the requirements of a future energy market. It is shown under which requirements the respective properties are fulfilled and how the decision of the technology can influence the properties.

5.1 Decentralization

The idea of decentralization in energy markets is the integration of smaller energy providers into the market and, based on incentives for prosumers, a better coupling of grid congestion management to the market mechanisms. In contrast to that, decentralization in the scope of DLTs describes the removal of powerful central units in the market system with a high amount of independent participants, also called nodes, involved in the consensus algorithm.

Generally, this is achieved through a P2P network. In a public blockchain every validating node has the same rights and takes care of an entire copy of past transactions. For efficiency reasons, transactions are typically grouped to blocks before they are updated on the blockchain. Changes will be flooded into the network and will reach every node eventually. If the majority of the validating nodes accept this change, this state becomes automatically the new state of the blockchain, i.e. consensus has been reached. This property is often explained as a democratic system, as the majority decides which transactions are valid without a central coordinator.

The idea of completely abolishing central coordination through DLT does unfortunately not fit to the energy market. The trust in grid operators to enable the power flow exists physically and cannot be removed through a digital system. Someone has to take care of the physical connection to the grid, so there is and will always be a centralized (and trusted) entity for all participants.

5.2 Available Trusted Party

The energy market is tightly coupled with the real power flow. Market participants are therefore known by each DSO, while the DSO is trusted by each participant to enable energy transmission through the power grid. Additionally, the grid operators have the right to disable parts of the grid as a last resort, to ensure a stable operation. As a trusted party exists and participants have to be known and capable to trade energy, a trustless public ledger is not needed for the energy market [42].

The potential benefit of a trustless ledger, if it would exist for the energy market, vanishes when the consensus is tied to permissions and membership, which is managed by a single authority [33]. Unfortunately, the use of permissioned blockchains is less efficient and scalable than modern database technology [29] [26].

5.3 Oracle problem

P2P markets need trusted meter values, to proof that the energy generation/consumption matches the forecast. The need for a tamper-proof data collection is very important for the integration between a real world system and a digital system, also known as the oracle problem [6].

In current systems the possibility to provide wrong electricity meter values exists too, but the personal penalty people are risking outweighs the benefits as they are personally known to the electricity provider. A market, where wrong measurements could be provided by fraudulent participants, could become unstable and cause power outages, while the malicious actor can earn a lot of money. In a trustless system, the fraud would be very hard to revert. Acquiring private keys stored on devices cannot be prevented if physical hardware access is available, even when the keys are stored on a Trusted Platform Module (TPM)[10].

5.4 Uncertainty of Time-Critical Transactions

If multiple new states are flooding through the network, the state which is accepted by the majority automatically becomes the longest chain. Other states will only be accepted by a minority and result in a shorter side-chain, that will be abandoned after future new states, because the minority will notice that their chain won't be longer used for new blocks.

As nodes can never be absolutely sure to be on the main-chain, a transaction is never totally consistent, still the probability rises with every additional block, as a longer chain only differs by the latest few blocks. This is a result from the probabilistic consistency of blockchain technology. The question, how many blocks should exist additionally, so that the probability that it has been issued to the main-chain is high enough, varies on the security needs.

For the energy sector, this creates additional friction, as transactions issued shortly before the deliverance time might be valid, but could also be invalidated through a contradicting transaction. The uncertainty, whether a transaction is valid at the stated delivery time, creates a large risk for spontaneous transactions. A system with a long duration for transaction finality does not fit the requirements for energy trading.

5.5 Forgery and Censorship Resistance

There are three malicious behaviors that blockchain technology is designed to prevent, which are explained below

Omitting sent Transactions. In centralized systems, participants can be excluded from writing by blocking their public key. In contrast, omitting sent transactions is impossible for blockchain technology, when multiple workers are included in the consensus finding. This benefit is lost when all quorum members can be influenced from one authority, as it is the case for Proof-of-Authority (PoA) blockchains.

Forge Transactions. When using asymmetric encryption it is not possible to forge a transaction which is signed by the private key which is only known to the participant. This is a common feature that is present in every use of asymmetric encryption.

Changing The History. Blockchain projects often advertise the property that stored data will continue to be tamper-proof in the future [27]. Due to the work done in Proof-of-Work (PoW) it is not efficiently possible to change the order of past transactions, add or remove parts of it. This is accomplished by linking hashes of past blocks together in a merkle tree. Alteration of past blocks would result in the need of rehashing all the following ones. All changes must be accepted by a majority of validating nodes before becoming the new ground truth.

The cost of rehashing is equivalent to the difficulty in the consensus finding. As there is no difficulty in PoA the rehashing process can be efficiently done, which makes it affordable to change the history if a fraudulent majority exists [33]. Yet, major changes in the history can be detected by every node that stores the whole blockchain history, not only by the participants of the consensus.

Concluding the larger the amount of independent and non-faulty nodes participating in the consensus algorithm of the blockchain network is, the higher is the probability, that alterations of the blockchain won't be accepted. While a public decentralized market has great forgery & censorship resistance, a private or permissioned blockchain does not necessarily guarantee these properties.

5.6 Security

DLT is often advertised as more secure due to the immutability and openness of the system. Yet malicious clients can exploit bugs in the blockchain protocol, the client or smart contracts which is a major issue [7]. Private keys can be compromised the same way as with every other system. The transparency allows code and contracts to be audited, but obscure code can add unwanted behavior, which is hard to detect[1]. Also, the data validity is only as strong as the security of the signed measurements. Rotating signature keys to reduce the period of validity, and therefore the time available to brute-force a key would be a measure to secure signatures [13]. The use of blockchain does not per se provide an advantage for the security of the program code, as the above list of exploits shows.

5.7 Privacy and Market Anonymity

In public blockchains the participants only need an asymmetric key pair to trade, which is generated without a link to an entity. Furthermore, every node can see every transaction and the involved addresses within a public blockchain. So transactions and funds are traceable through the network from every participant. This can be altered in private or permissioned blockchains with different access-levels.

In the energy market the participants must be known and mapped to the corresponding real world electricity meters resulting in a loss of complete anonymity. The grid operator must be able to identify the location of the node, but other market participants don't need this information. This can prevent market discrimination, as it is important to communicate the orders anonymously so that bids and asks can not be matched to a specific market actor. Still, when historic trades are publicly available, usage patterns can be extracted to identify the trades and strategies of individuals.

5.8 Consistency & Scalability

An important aspect of every centralized or decentralized system is the consistency. For every distributed system the CAP-Theorem holds, stating that only two of consistency, availability and partition-tolerance can be achieved at the same time [16]. The communication overhead for a distributed system with n nodes rises with every node, making scalability harder, as it takes longer to achieve to a consistent state.

Most public blockchains like Bitcoin focus on high decentralization and high consistency with large block intervals, secured through PoW. This option is not feasible for the energy market, because the scalability is limited and the consistency becomes probabilistic (see 5.4). There are scalable solutions for financial blockchains with second layer protocols like the Lighting Network for Bitcoin, that lower the amount of transactions on the blockchain through preallocation and aggregation [31]. Which cannot be done for the energy sector, because energy cannot be allocated ahead of time.

It would be beneficial to the grid stability, if energy market transactions were as focused as possible on the local distance in order to reduce the energy exchanged with other grid sections. If most transactions involve only a few locally connected participants, one can break down the scalability requirements to each subnetwork.

This idea can be found in a fairly new DLTs called Directed Acyclic Graphs (DAGs). DAGs are an example for high scalability and decentralization. They use independent sub-graphs, that can be build concurrently and get merged in the future. This results in a lower consistency in the network, because not every node knows the state of the entire DAG at the same time, which is also known as eventual consistency.

5.9 Summary

The integration of blockchain into the energy market has many challenges, which are

1. Removal of trusted authorities is not feasible
2. A trusted third party must be available for every participant
3. Tamper-proof electricity meters are needed
4. The eventual consistency does not fit the energy model
5. Append-only property of DLTs secures history
6. Modification of past blocks is efficiently possibly for permissioned systems, but can be detected
7. DLTs does not bring a security benefit per se
8. Market participants are only pseudonym, market anonymity is very hard
9. Efficiency of a decentralized system decreases with increasing number of participants

Related concepts and how they adhere to the outlined challenges are described in the next section.

6 RELATED WORK

Different concepts to enable P2P or DLT for the energy market were proposed recently.

P2P markets generally allow for individuals to trade energy between two individual parties. Depending on the interpretation of P2P, the communication for the trade must be without a third party, while other concepts also see Community-based markets as P2P. Further analysis of different P2P markets is done in [34].

The projects can be divided into different categories:

Gossiping. A gossiping market as described in [8] allows communication without a structured route. Information is shared by gossiping between the nodes[45]. This market type does not need centralized communication channels and iterates to stable state[39]. There has also been a lot of research for gossiping protocols, which in general gets slower for larger systems [5].

Centralized. The current centralized markets are using energy providers as aggregators to keep the number of market participants low. Typically, the participants have a fixed price for long time

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[1] https://u.solidity.cc/

[2] OTC, Futures, Day-Ahead, Intraday, FCR, aFRR, mFRR, Day-After

	European framework	DLT-based market [43] [38] [28]	Gossiping Market [8]	Two-Step Market [20] [37]	Smart Grid Control- Grid Code [30]	Proposed Concept NAP2PEM
Trust Origin	EEX	DLT operator	operator	pool/market	grid operator	TSO
Metervalue Trust	meter operator	○	○	tamper-proof device	○	signed meter values
Delivery Obligation	●	●	○	●	○	●
Market matching	Market/Merit-Order	announcement	announcement	pool/market	○	free market
Scalability (network traffic or storage)	single market stores data	every participant stores copy	exponential communcation overhead	each pool stores data	not stored	tree-like structure scales well
Flexibility Integration	○	◐	◐	◐	grid code	direct price signal
Congestion Management	redispatch	○	○	○	○	grid fees
Market Stages	multiple[2]	continous auction	iterative auction	wholesale and community	frequency price signal	energy and balancing
Reserve Energy in Advance	●	◐	◐	●	●	●
Market Members	big plants and EPs	all participants	all participants	operator and participants inside pool	●	●

Table 1: Feature comparison of energy market models
Legend: ● - fully exists; ◐ - can be added, but not provided; ○ - not integrated

periods, while the aggregators take the risk for the fixed prices. An incentive for customers to use their flexibility is not given as the cost is independent of the current demand. At the wholesale market multiple layers with different products exist. For example offers for a given time can be linked to other offers, so that both have to be bought together. A centralized price clearing can take place shortly before the energy is consumed/delivered. The grid congestion is respected through re-dispatching offers after market clearing. Balancing energy is provided through a separate balancing market. This concept is currently in use at many Power Exchanges [32].

Two-Step Market. In a two-step market, a decentralized market exists in one area, and communicates with other market participants on the upper layer [21]. This concept allows integration into the existing market concepts. It can be seen as a Peer-to-Pool concept, where the decentralization is locally coupled. Good analysis of community based markets is done in [35]. A P2P-based market where peers buy reserve energy to avoid a deviation penalty in the community is proposed in [24]. Typically, the wholesale market stays the same and allows to buy and sell remaining energy and only a part of the grid trades at the P2P step. The P2P pricing mechanism is often iterative.

Blockchain based Market. Most projects focus on the P2P ability or the compatibility to the current regulatory framework. Different 'Proof of' Mechanisms are used to create the distributed consensus. A comprehensive review of existing projects using blockchain for energy trading is done in [4].

Many projects lack detail on how the peer-to-peer market clearing is organized or assume the central coordination of a single entity, rendering the trustless structure useless. Other concepts are using blockchain technology but are neither discussing the trust generation for the meter values, nor what the incentive of people is to run needed full nodes, which is one of the reasons why market adaption is missing in many cases.

Grid Code Based Market. There are also grid code concepts which are using the network frequency directly as a price signal as the concept presented in [30]. Here the demand response mechanism happens implicit through the monitoring of the network frequency. Fast fluctuations of the network frequency can be covered through averaging. This allows for a market mechanism without data collection, yet all electricity meters must meet high standards as they are used to bill the energy. Furthermore, grid congestion can not be respected, as the congestion of a line is not known from the frequency.

The features of different P2P-based markets are compared in Table 1. It can be seen that the current European framework does only include big market players. It would not scale for significantly more participants as it uses a single market. For DLT-based market, participants must know each other, or know someone who knows. It is often unclear where the announcement comes from.

7 PROPOSED ARCHITECTURE FOR A P2P ENERGY MARKET

Based on the aforementioned properties of blockchain technology, a novel approach is presented in the following. In a P2P market, all consumers and producers are equal participants. From a high level perspective, they should have the same rights and duties, regardless of the amount of traded energy. The proposed concept identifies two fundamentally different roles for the energy market: Participants providing balancing energy and those that only buy or sell energy based on the market and grid situation. Any provided flexibility can be used as balancing energy to keep the grid stable. Balancing energy must be traded with participants that deviate from their predicted energy production or consumption to ensure that the physical network frequency is stable.

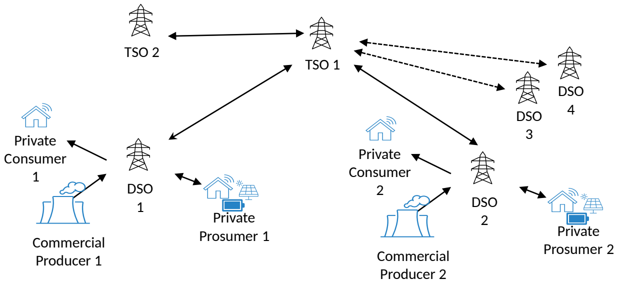

Figure 4: Hierarchical grid structure of the proposed market architecture. Every grid operator commissions a market operator. The market hierarchy resembles the grid hierarchy

In the following, a novel concept for a generalized P2P-market is discussed, which has simplicity in mind but still covers all the edge cases of an electricity market.

7.1 Scalability

To facilitate market mechanisms that scale for a high amount of participants, the market is hierarchically structured. Tree-like structures provide very good scalability and allow complexity reduction into small subproblems. This is beneficial to simulate the market for subgrids, as well as larger grids. The proposed structure reduces the required communication by filtering offers which are expensive including grid fees. Therefore, as most interactions happen locally, upper markets do not need to know of trades happening within a local market. Only the cheapest bids and offers (including grid fees) are sent to the upper market and are continuously updated.

The Grid from Ian Foster describes a grid architecture for computers, based on the power grid [15]. The Grid facilitates the set-up of a multi-institutional infrastructure based on the concept of virtual organizations. Virtual organizations were built on an agreement on access control and accounting. The idea of a virtual organization is now brought back to the power grid. Standardized X.509 certificates as used in TLS allow for the creation of a tree-like structure of markets which can be verified through the certificate chain. The proposed hierarchical structure is inspired by DNS and makes heavy use of digital signatures. The interconnected power grid can operate a root certificate authority of the virtual organization, i.e. it defines the root of trust. Trust is then delegated to grid operators, which can delegate the market processing to a trusted party or operate the market for the subgrid themselves. The market provider must be commissioned by the network operator to carry out fair transactions and respect the grid fees of the DSO in its market area. While classical certificate chains can be used here, proxy certificates as described in [40] are a potential way for the market to issue certificates for all participants of the market. The root certificate authority creates certificates for all TSOs who then delegate the market operation to a market operator. The market operator creates proxy certificates for the DSOs in their grid and large generation plants, etc. Proxy certificates have the advantage of a very limited lifetime compared to classical certificates, which facilitates a very dynamic market constitution. Additionally, the usage of such proxy certificates limit trades to a specific connection point by assertions listed in the extension field of the certificate. Also the proxy certificate allow to identify every trading participant and its origin market, through the trustchain.

7.2 Market Interconnection

Just like distribution grids are interconnected with other electricity grids through a transmission grid, the corresponding markets are connected similarly. The smaller markets forward the trades happening at the lower layer to the transmission market, which filters only the cheapest offers from all connected participants to maintain scalability and forwards those back to all participants. Each market streams the cheapest offers to its participants and the upper market. This allows participants from small markets to trade energy with big power plants on the transmission layer or participants from other subgrids. The hierarchic trading topology is illustrated in Figure 4.

A new submarket can be operated behind every legitimate node. A node can be viewed as an acting entity in the presented market approach. Thereby, a valid participant can take the role of a grid operator and create a power grid behind its node in his responsibility. Then, a market operator and meter value storage has to be provided accordingly as a responsibility for the participants connected to the submarket. This allows for the creation of smaller communities, for example to trade within a tenants community. The total trading amount of a market operator must be balanced at any time, so that the sum of all orders matches the demand. This is controlled be the respective upper market and includes the handling of reactive power losses, which must be bought by the grid operator beforehand.

7.3 Tamper-proof Metering

Electricity meters must have the ability to correctly report the amount of electricity consumed or generated for each time interval to a meter data value. To ensure that the meter data read out by the devices is trustworthy, a certificate signed by a trusted entity must be present on each device. Clearly, for any remote firmware updates further security mechanisms are required.

A Public Key Infrastructure (PKI) is operated by a responsible entity like a smartmeter-gateway-administrator in Germany. An issued certificate with a signing key is installed on the device by the trusted entity, that is typically also responsible for assuring a correct calibration of the device. The certificate in use must match the chain of trust of the market as described above. When commissioning the grid connection point for the first time, an electricity meter approved by the grid operator must be installed. The grid operator is the only entity which must know the public key and the exact location of the installed meter.

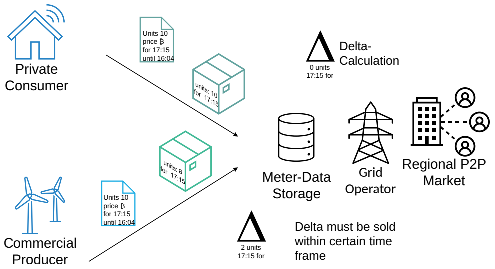

Figure 5: Electricity meters are used to calculate the deviation. The three entities metervalue storage, grid operator and market operator are responsible for a balanced sub grid

For the market operator, this ensures that a certified electricity meter is available at each market participant's premises. The signed electricity meter readings must be stored in a metervalue storage that can be accessed by the market to perform billing. While eventual consistency should be enough for the storage in theory, this simplifies scalability through scale out, the grid relevant power flow is rather locally processed. Hence, stronger consistency models can be used here, since scalability is less important here. A sample message would consist of (timestamp, generation-meter, consumption-meter, signature). By using separate electricity meters for generation and consumption, the meter values are stored based on the monotonous increasing timestamps, which allows for simple integrity checks of the data. Also column-based NoSQL databases might be used here, since the monotonous increase of time nicely fits their concept of maintaining sorted columns.

The grid operator is in charge to commission the three operative entities of a grid:

- grid operator
- market operator
- meter data storage

As the values are signed by the electricity meter, they can not be altered by the meter data storage. They can only be dropped, as it would happen with a connection loss. This problem could be easily spotted and there is no incentive to do so, as the data would be sent again.

7.4 Energy Trading

To trade energy at a given time-slot, a participant can bid or ask an amount at the market. The message is enclosed in a signature and a timestamp until when it is valid. This removes the need to withdraw a message, as offers automatically expire.

All transactions at first only exist virtually. The regulatory framework must ensure that a virtual claim also gives rise to an actual cash flow (for example monthly bills). Clearly, both parties of an agreement must have access to the underlying transaction, or to a relevant clearing partner record. Alternatively, a pre-paid structure might be built where each participant has to top up a virtual account at the market.

In a P2P transaction, the signature of participant A must be included in a payment to B. The transactions must therefore be coupled, but for this A must know the offer of B beforehand. This is a different scenario than the market automatically balancing bids when the bid is higher than the ask. So there are two modes: direct matching and a pay-as-offer market.

Unit Sizes. Big power plants would sell large amounts of energy at once, resulting in large transactions, which can not be bought by participants with a small demand. Therefore, bids must either be splitted into small amounts of energy (e.g. 1 kWh) which are handled individually or a partial matching of an offer must be possible. This would allow for multiple consumers to buy a part of a large offer. As it could be intended to sell in large chunks as partial offers cannot be economically served, only the first option is respected currently.

Direct Matching. For the direct matching, participant "A" sends participant "B" a sell offer ((isBid, amount, price, time-slot, valid-until) signature). An offer has a minimum availability requirement, so that the refresh rate of offers is bounded. B can sign this message to give his consent and must send it to the market before the valid-until timestamp is due. The market can then disambiguously identify if the offer from A has been already accepted by other participants. Other markets can efficiently find the specific peer by following the tree-structure to the issueing market. This allows P2P communication and off-market behavior. Still the grid fees are added on top when the transaction reaches the market.

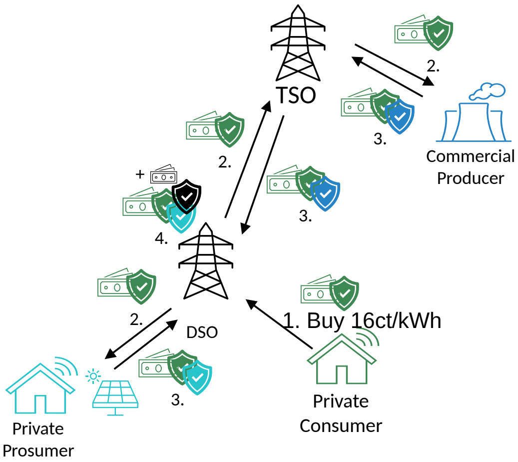

Figure 6: Direct matching is time dependent - locality is preferred. 1. Private Consumer announces buy offer to the dso market, signed with its private key 2. DSO distributes new buy offer to participants and upper market 3. Participants send acceptance back to originating market, signed with their private key 4. acceptance from prosumer reached the DSO first and is accepted by the DSO through signature and published

Pay-As-Offer Market. Otherwise, a sell offer ((isBid, amount, price, time-slot, valid-until) signature) can be sent from participant "A" to the market. The market broadcasts the cheapest available offers at its market to all his market participants and the upper market. Participant B can then send a corresponding buy offer to his market. If the bid is higher than the ask price, the market then matches bid and ask. The transaction origin is verified and the two messages are signed by the market to provide reliability for B and A that the transaction takes place. Finally, the price of the offer is cleared, with additional grid fees paid by the buyer.

For intra-market communication, a fixed amount of the cheapest offers and bids is sent by every market to its participants and upper market. Those are continuously updated through flooding. By ordering the entities by price, required merges of any upper market layer can be implemented more efficiently. Indeed, participants who try to buy offers from a market which is a few hops away have a strategic disadvantage through higher latencies, as their offer approval has to reach the issuing market before other approvals. This further supports the local market payments as it is beneficial to trade with near market participants. To prevent grid congestion, additional load dependent grid fees can be applied.

It is important to note that an offer sent to the market is matched if the originating market signs the accepted message as seen in Figure 6. This supports the P2P approach, yet creates a trusted relation for all participants. If a market already received an acceptance from another participant, the acceptance from the later paricipant is invalidated. As this can happen multiple times, the participant can be starved, if he continues to trade at a market which is far away and has many hops inbetween. Transactions which are not related, do not need to be globally sequential consistant. Sequential consistency is only important within a market, where it is enforced as it is a single authority with access to all transactions of its direct participants.

7.5 Grid Fees

To integrate grid-serving behavior into the market, a grid fee must be paid by the buying participant depending on the caused network load on every affected grid segement. The grid fee also includes a transaction cost, since the digital infrastructure proposed here must be implemented, e.g. the Transmission System Operator (TSO) provides a market interconnection and aggregation service that is affected by updates flooded by the lower layers.

The distribution grid operator guarantees the operation of the network and provides enough capacity to avoid congestion at a larger scale. This supply of services has to be paid by everyone using the network. While congestion is not good for the stability of the network, the maximum utilization is demanded to maximize the profit of the DSO. Those conflicting goals have to be considered for a possible price curve.

Sharing a limited resource, like a high-demanded grid line, is a tragedy of commons and equally sharing the cost would still have an incentive to use more of the available capacity for each individual participant. Auctioning the available capacity could be a solution, but is not possible in the electricity setting, since placed orders cannot be rejected. Furthermore, a possible auction would not take place at a single time-slot and is instead distributed across the whole time in which orders can be set.

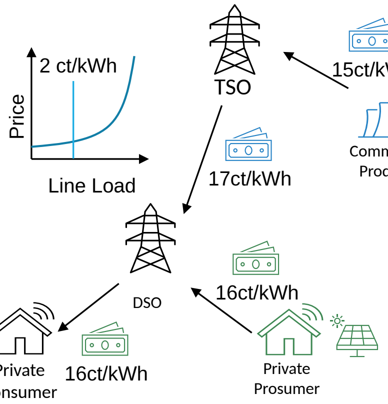

Figure 7: Grid fees are paid according to the usage of every line in the hierarchic structure

The tragedy of commons can be avoided when the participants causing congestion pay higher grid fees. Therefore, the grid operator calculates the fee for every line depending on the reserved load from placed orders. The dynamic grid fees can be seen as the regulation signal, which is enforced by the grid operator, who monitors the available capacity of each grid line and adjusts the grid fees accordingly. The resulting price curve is depending on the utilization, thereby distributing the grid cost according to the first come, first served method. Transactions get lower fees when the utilization is low than transactions completed at a high utilization. Different approaches for the calculation of the congestion cost are discussed in [23].

The impact of the price curve can be seen in Figure 7. Here the commercial producer can generate energy for a price of 15 ct/kWh. Due to the forecasted load of the lines on the path to the DSO, 2 ct/kWh are added as a grid fee to this offer. Therefore, the energy generated by the private prosumer is cheaper than the power plant in total. The price will become very high for the last percentages of network usage as 100 % utilization is a rare case with a high price. The price can become lower if energy is sold in the contrary line direction, this can also cause negative grid fees.

The incentive of the grid operator is to earn money through grid costs. Therefore, transactions within the subgrid are preferred as line cost to the upper market is received by the upper markets grid operator and a transaction within the network results in more revenue for the operator. This also prevents the grid operator from taking high grid fees as he benefits most when it's cheaper than an external trade. Furthermore, participants can control and compare the announced grid prices with other DSOs to check the legitimacy of the prices.

After the offers of a time-slot were executed, the market accesses the meter data storage to calculate the deviation between the traded energy and the actually used as seen in 5. The deviation must be sold in a second market stage afterwards, which is described in the following section.

7.6 Balancing Energy and Deviation Trading

As participants buy and sell energy for future time-slots based on a forecast or schedule, the actual generation/consumption does not always match the forecasted values. For those cases, balancing energy is needed.

For a given time interval t, the traded energy E_{market} does not fit the actual energy flow E_{actual}. Thereby causing the deviation $\Delta E = E_{market} - E_{actual}$ which has to provided as balancing energy.

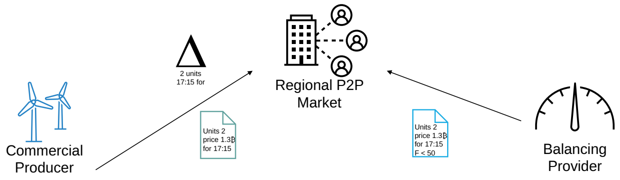

Figure 8: Concept for a P2P balancing providers

This is handled by balancing providers with a electricity meter capable of monitoring the network frequency f_m and the electricity flow for balancing energy E_b. Each participant providing control energy creates a balancing benefit if energy is produced when the frequency is below the target network frequency f_t (typically 50 Hz or 60 Hz) or consumed if the network frequency is higher than the target:

$$(f_t - f_m) \cdot E_b > 0$$

On the other hand an additional payment from the balancing provider is needed if

$$(f_t - f_m) \cdot E_b < 0$$

as this places an additional load on the network.

The revenue a balancing provider creates relies on the probability of providing balancing energy at the right time faster than other balancing providers. Each balancing provider can proof the created benefit with signed meter values and receive money by selling the beneficial energy to the market. As the amount of balancing energy produced does exactly fit ΔE for a given time, all the balancing energy has to be paid by participants that were off target, so a free market does not exist. It is obligatory to buy, so that either the price or the guaranteed amount must be fixed for balancing energy. As the amount can not be determined beforehand, a set price must ensure that incentives are high enough to produce enough balancing energy. Both approaches have pros and cons, but in both cases the grid operator has to set the price or amount, based on a prediction for balancing energy. In this approach, the fixed price is investigated, but a fixed amount which gets auctioned is also possible.

8 CONCLUSION AND PERSPECTIVE

In this paper the flaws of using blockchain technology in the energy market are discussed. It can be summarized that blockchain technology does not bring a benefit for energy markets as all market participants must be registered and central monopolies are needed for the operation of an electricity grid. Instead, the usage of the hierarchical structures allows to propose a novel concept for a decentralized market which respects the aspect of congestion energy, basic concepts of nodal pricing as well as the union of the physical electricity market with the accounting layer. The regulatory framework is simplified to three different market roles and general market participants, who can also act as balancing providers.

The challenges of the electricity market from subsection 4.3 are respected. An incentive for participants to behave in a grid-serving manner is implemented in the architecture by, among other things, introducing load-dependent grid charges. The market entry barriers are removed, so that every participant can trade energy and even create a separate subgrid, while still maintaining the scalability by reducing the amount of offers forwarded. Balancing energy can be provided by participants with fast responding balancing capabilities. Also key points from subsection 5.9 are considered in the proposal. Tamper-proof electricity meters provide trustworthy values on which market processes can be based. The market anonymity can be established if only the needing participants can see sensitive information. The scalability of the decentralized is provided by using a tree-like structure.

Further research has to be done to investigate the behavior of the proposed concept in a real world scenario. This is achieved by deploying the concept in parallel to the existing structures for five demonstrator projects within a research project.

The question of the best strategy for a price curve of the grid fees as well as the market stability have to be investigated. The single point of failure of the current framework is divided, yet the impact of a small outage in the proposed framework must be researched. The legal framework of new P2P markets is not considered in this paper but is evaluated in [9].

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