Blockchain in the Energy Industry – Comprehensive Analysis of Potential Use Cases

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***Abstract*—Various applications for blockchain technology in the energy industry have been proposed in recent years. In order to systematically assess all relevant use cases in this field, potential application scenarios are collected by literature review and expert survey, clustered and evaluated regarding economic and regulatory potential. This approach yields five promising use cases, which are subsequently examined in more detail: labeling, asset logging, supplier switching, verification of control reserve and peer-to-peer trading. The analyses show that the technology shows its strengths mainly for application areas which involve various stakeholders and require a secure and trusted information and communication infrastructure.**

***Index Terms*--blockchain, energy industry, use cases**

I. Introduction

In recent years, the application of blockchain technology to the energy industry has been widely discussed. Several use cases have been proposed by different stakeholders, which utilize the key features of the technology to varying extent. In order to identify promising use cases for further evaluation and implementation, a comprehensive overview, analysis and evaluation of potential blockchain applications in the energy sector is presented.

II. Methodology

The applied methodology consists of four steps. Firstly, the underlying technology is thoroughly analyzed regarding its specific features, value propositions and potential future improvement with special regard to the requirements of the energy industry [1]. Afterwards, potential use cases are collected from both a literature review and from 11 workshops with in total 161 experts of partner companies [2]. These use cases are subsequently clustered and evaluated regarding their potential impact to the affected stakeholders, to their individual business model, to the energy market [3] and energy industry in general. The evaluation also includes chances and risks, regulatory compliance and adjustment requirements, further legal implications like data protection and general contract law, possible options for practical implementation and as a conclusion the overall disruptive potential. As a last step, the most promising use cases according to these criteria were selected and further elaborated in cooperation with the project partners.

III. Technical Features

Blockchain technology consists of a distributed ledger in which data is stored in discrete blocks. Due to the distributed nature, data integrity and transaction order are guaranteed by so-called consensus mechanisms. These are mainly based on hash functions and cryptographic elements, which are also used in other areas of IT security. The first consensus mechanism in use was "proof of work" and is responsible for the high energy consumption of blockchain technology. New concepts are already being tested or developed. The first and currently most popular application of blockchain technology is digital payment ("crypto currencies"). However, the technology offers a basis for many applications in a variety of sectors including the energy industry.

In addition to the decentralized storage of data, the blockchain technology has also been able to execute programs since the development of the Ethereum blockchain and can thus, for example, map contract structures and process them automatically. These so-called "smart contracts" are essential for a large number of applications of blockchain technology, especially in the energy industry. On their basis, distributed apps can be developed in order to provide users with access to the blockchain. Blockchain software can be set up in different ways, e.g. access to private blockchains for external third parties can be prevented. However, hybrid models, for example between several companies, are also possible compared to the open solution of the majority of crypto currencies.

The strengths of the technology lie, among other things, in the transparency of the transaction process, its tamper-resilient characteristics, the possible pseudonymity and a high degree of availability. Today, limitations still exist above all in the areas of scalability, transaction costs and speed, anonymity and interoperability as well as energy consumption. Current developments show that a large number of approaches are currently being developed to overcome these limitations. These include Sharding, State Channels, Sidechains, Zero Knowledge Proofs or Ring Signatures.

We would like to thank our partners Innogy, SMA, Stadtwerke Augsburg, Thüga, TransnetBW, VBEW, Verbund and Illwerke VKW for supporting this project.

The potential applications of the technology are manifold and include many economic sectors. Blockchain technology can serve not only as means of payment, but its distinctive features can be utilized in a variety of processes to

- create trust,
- substitute intermediaries,
- handle decentralized (peer-to-peer) interactions,
- enable transparency,
- document ownership,
- create anonymity or pseudonymity,
- ensure the security of digital transactions,
- facilitate micro-transactions,
- automate processes,
- optimize processes and,
- accelerate data exchange and billing.

Based on these properties, a wide range of use cases can be deduced. Blockchain technology can have an influence on copyright and intellectual property, improve or enable supply chain management, sharing economy and decentralized management of digital identities. The use of blockchain technology as a crypto currency also offers opportunities to create alternative financing and payment options.

IV. Resulting Use Cases

The previously described methodology proves useful for collection and evaluation of use cases. 91 potential blockchain applications were identified that affect virtually all stages of the value chain. The evaluation criteria allow selecting use cases, which utilize the main advantages of blockchain systems like decentralization, transparency, security, availability, immutability and automation and at the same time evince considerable potential regarding both implementability and impact. This yields the following clusters for further analysis: labeling, the blockchain-based recording of generation and consumption data in order to track for example renewable energy or geographic origin [4], asset logging, the immutable storage and automated processing of operation and maintenance data of specific assets, improved market communication based on blockchain infrastructure [5] and verification of ancillary services.

A. *Labeling*

Electricity as a homogeneous good does not have any quality characteristics and differentiation possibilities per se. Nevertheless, the purpose of electricity labeling is to enable a distinction between the types of generation and an allocation to consumption.

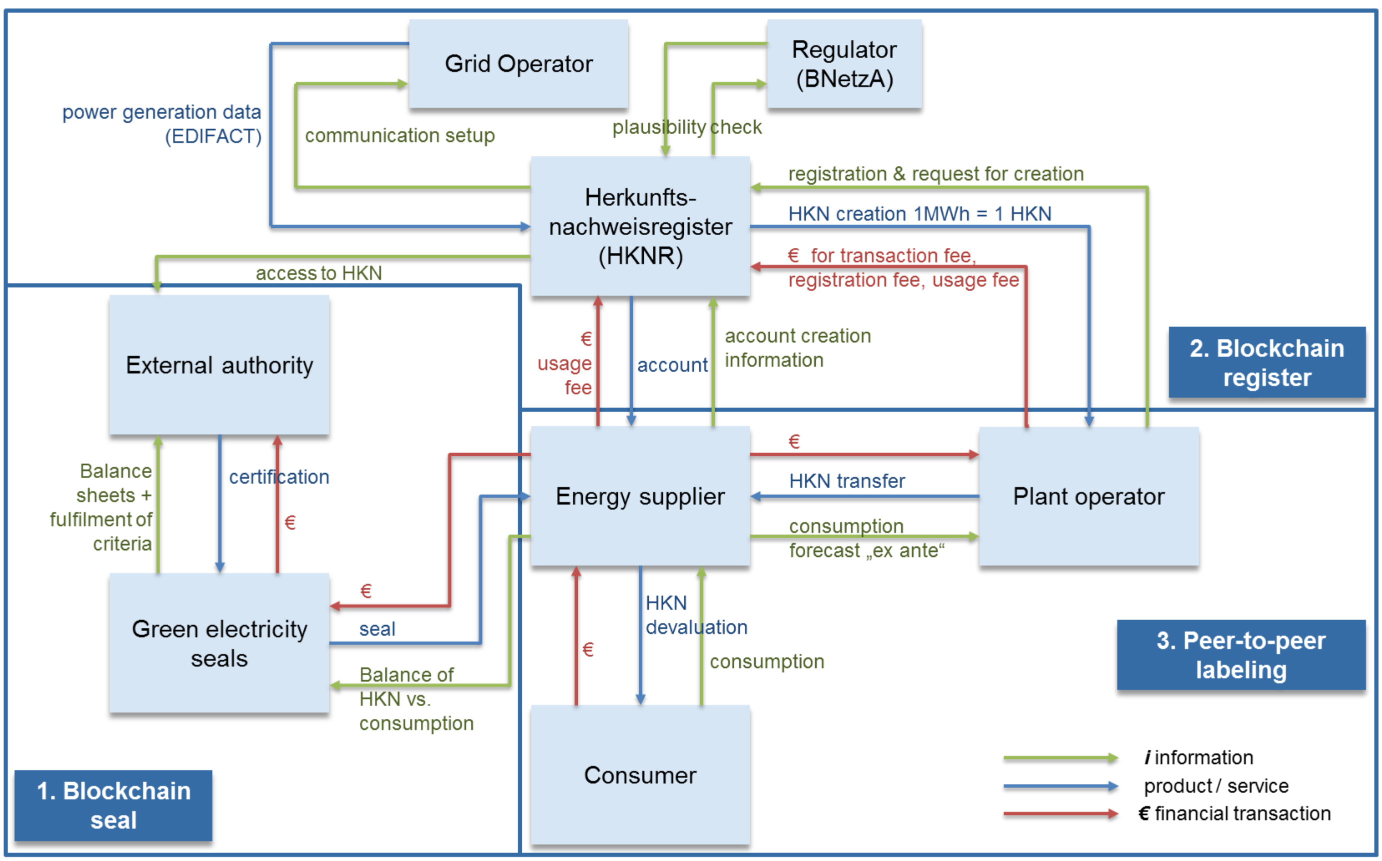

Figure 1: Green electricity certification – status quo and possible conceptual approaches for blockchain implementation

The legal basis for electricity labeling in Germany was passed in 2005 (§ 42 EnWG and § 78 EEG) and introduced a system to allocate and trade so-called “Herkunftsnachweise” (HKN). These HKN are designed with quite long balancing periods of one year and the precondition of 1 HKN representing 1 MWh of renewable energy. However, this leads to a temporal decoupling of consumption and assigned generation. Therefore, the system offers no direct incentive for a consumption-oriented expansion of renewable energies. As a result, the current system is accused of "greenwashing" [6]. An adjustment of the current approach could improve the current system and lead to higher transparency.

1) Status quo

The decoupling of proof of origin (“Herkunftsnachweise”, HKN) and supply contracts currently makes it possible to freely trade "green electricity certificates” within the European market region. In Germany, the market place is organized in the “Herkunftsnachweisregister” (HKNR) of the Federal Environment Agency (Umweltbundesamt UBA). Combined with the quite complex way of allocation, this implies several risks of intransparency to the customer. Although there is a large number of quality seals issued by external authorities, the non-uniform certification criteria make it difficult to compare these seals. [7]

One quite prominent example for this intransparency is related to regional oversupplies of electricity from renewable energies, e.g. in the Scandinavian countries due to high hydropower generation [8], [9], [10]. These certificates are offered to the market, purchased by energy suppliers (e.g. in Germany) and allocated to their customers' electricity rates. However, the physical delivery does match the exchange of certificates. At the same time, a regional electricity customer (in Scandinavia) correctly assumes a physical “supply” of electricity from renewable sources; in accounting terms, however, the associated proof of origin certificate could theoretically have been sold to suppliers in southern or central Europe. Their electricity customers in return also assume a “supply” of electricity from renewable energies. In this respect, a more transparent implementation could enable the correct and temporally resolved allocation of generation and consumption. This could also make a valuable contribution to consumer protection.

2) Blockchain-based concept approaches

A redesign of the electricity labeling system should meet two basic requirements: On the one hand, it should be able to represent short balancing periods and on the other hand, it has to ensure complete documentation from power generation to consumption.

The basic characteristics of the blockchain technology allow an improvement of the current process. For example, certificates of origin and the corresponding amount of generated electricity can be documented transparently and inseparably on the blockchain. These time sequences can be documented in high resolution and the process can be further automated with the help of smart contracts. Three conceptual approaches have been developed, which start at different process levels of the existing electricity labelling (cf. Fig. 1) [2], [11].

a) Blockchain Seal

The first concept, based on the status quo of certification (in Germany), starts at the level of ex-post process evaluation of the current certificate allocation system. It therefore aims for quality improvement through the introduction of a blockchain seal that can provide a transparent and consumer-friendly assessment and overview of the various electricity suppliers. It shows the shortest implementation horizon and uses the blockchain-related technical features of transparency and manipulation security with high availability in order to guarantee the end consumer the correct allocation of sold electricity quantity and purchased HKN of the energy supplier. It starts at the ex-post certification level that currently is provided by certification authorities. As this concept only allows the assignment of 1 HKN for 1 MWh, it cannot fulfill the desired high-resolution documentation. Therefore, the added value is only in the automated substitution of external auditors. The concept can be implemented within the current legal framework and parallelly to existing processes.

b) Blockchain Register

The second approach starts at the communication and data management level with the goal of a transparent documentation of HKN with high temporal and allocation resolution. The blockchain register would therefore replace the current HKNR. Through direct trade of HKN on the blockchain, the market communication would be improved and administration expenditures can be reduced by process automation. Inefficiencies can be avoided by standardized system interfaces to the Blockchain. Direct information from the electricity supplier guarantees traceable and coupled allocation to consumption in any temporal resolution. The current relationship of 1 MWh = 1 HKN can thus be resolved, which also enables the improved integration of small generation plants in the future. Process optimization, standardization but also consolidation of the various national registers in the European electricity market in accordance with EU Directive 2009/72/EC is possible.

c) Peer-to-Peer Labeling

A more disruptive approach aims for a blockchain integration at platform level. Therefore, a new concept for electricity labeling through peer-to-peer proof-of-origin is developed. In this case, the labeling of electricity is not a singular event, but a dynamic process that directly assigns generation and consumption to one another in short time intervals. This enables an asset-specific and even regional allocation in an almost real-time manner. This approach could be realized as a value-added service for consumers and thus, enable significantly improved transparency with regard to the origin and availability of renewable generation. Furthermore, this type of platform can also serve as a standardized communication infrastructure for the implementation of further market processes [5] and enable further use cases such as regional direct marketing or PPA.

3) Technical proof-of-concept

As part of a research project, a proof of concept was implemented based on the Ethereum blockchain and feasibility has been demonstrated (cf. Fig. 2). In order to achieve a proper allocation, consumers and producers must

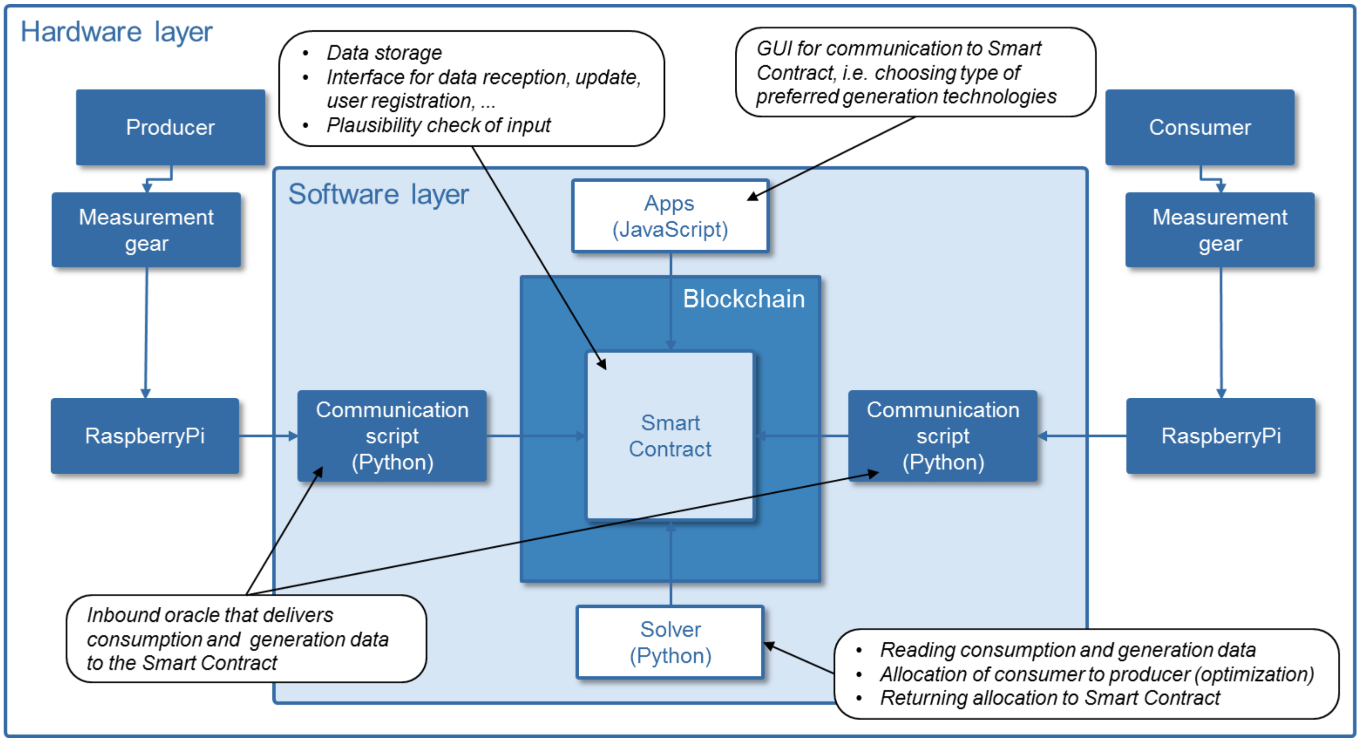

Figure 2: Design of a technical proof-of-concept for a Blockchain-based realization of peer-to-peer labeling

first be equipped with a hardware interface that transfers data to a smart contract at a fixed rate (in this concept: one transaction per minute). A Python script is used as a communicator between the interface (e.g. RaspberryPi) and the node. One node running an optimization script reads the data stored on the Blockchain and externally solves the optimized allocation. The solution contains the assignment of consumer and producer based on several parameters and is passed back to the smart contract [12]. In theory, this function could also be executed via smart contracts, but blockchain architecture is not (yet) designed for complex calculations. Therefore, the optimization is performed "off-chain", but correctness of the calculation is checked "on-chain" afterwards.

4) Summary

Within the context of increasing decentralization and digitization, the integration of small decentralized plants into the energy system will become more and more important. Today's processes will have to be adapted to these new conditions in the future. A peer-to-peer solution can offer an adequate alternative. Plants that are supported by the Renewable Energy Act (currently approximately 90 % of renewable generation in Germany) are not able to participate in the current system of HKN (cf. § 78 EEG). Nevertheless, an increase in the number of potentially participating plants whose EEG remuneration will expire can be expected. [13], [14], [15]

A redesign of the system could offer significant added value in terms of transparency and traceability of electricity flows for the consumer and thus, also an incentive for the further expansion of renewable generation plants. In addition, the use of a blockchain can rebut the accusation of green washing.

B. *Asset Logging*

Currently there are no general, uniform standards for the documentation and verification of asset data or asset-related processes (e.g. repair, maintenance). Usually only proprietary and often incompatible solutions are used. Nevertheless, detailed knowledge of the current condition based on historical events is necessary for the analysis of plant utilization and efficient operation. Furthermore, there are often regulatory obligations to transparently provide asset data to authorities. Also business models change due to digitalization, so the increasing relevance of asset sharing and service applications results in more frequent data exchange between stakeholders. In case of asset valuation, warranty or liability claims, a common data base as well as independent authorities to mediate are missing. [16]

This leads to the conclusion that especially within processes that include several participating parties, there is a demand for standardized data provision and unified interfaces. Therefore, an “Asset Logging platform” can be the solution, providing the middleware for a whole field of applications with a special focus -- but not limited -- to the energy sector.

1) Fields of application

The number of possible applications based on the data provided range from third-party services such as insurance or maintenance over standardized interactions with other market participants or regulators to in-house usage of the data. One example are resell and second-life markets, where the operating history, in addition to the current condition, is decisive for an objective evaluation of the asset value. Using a

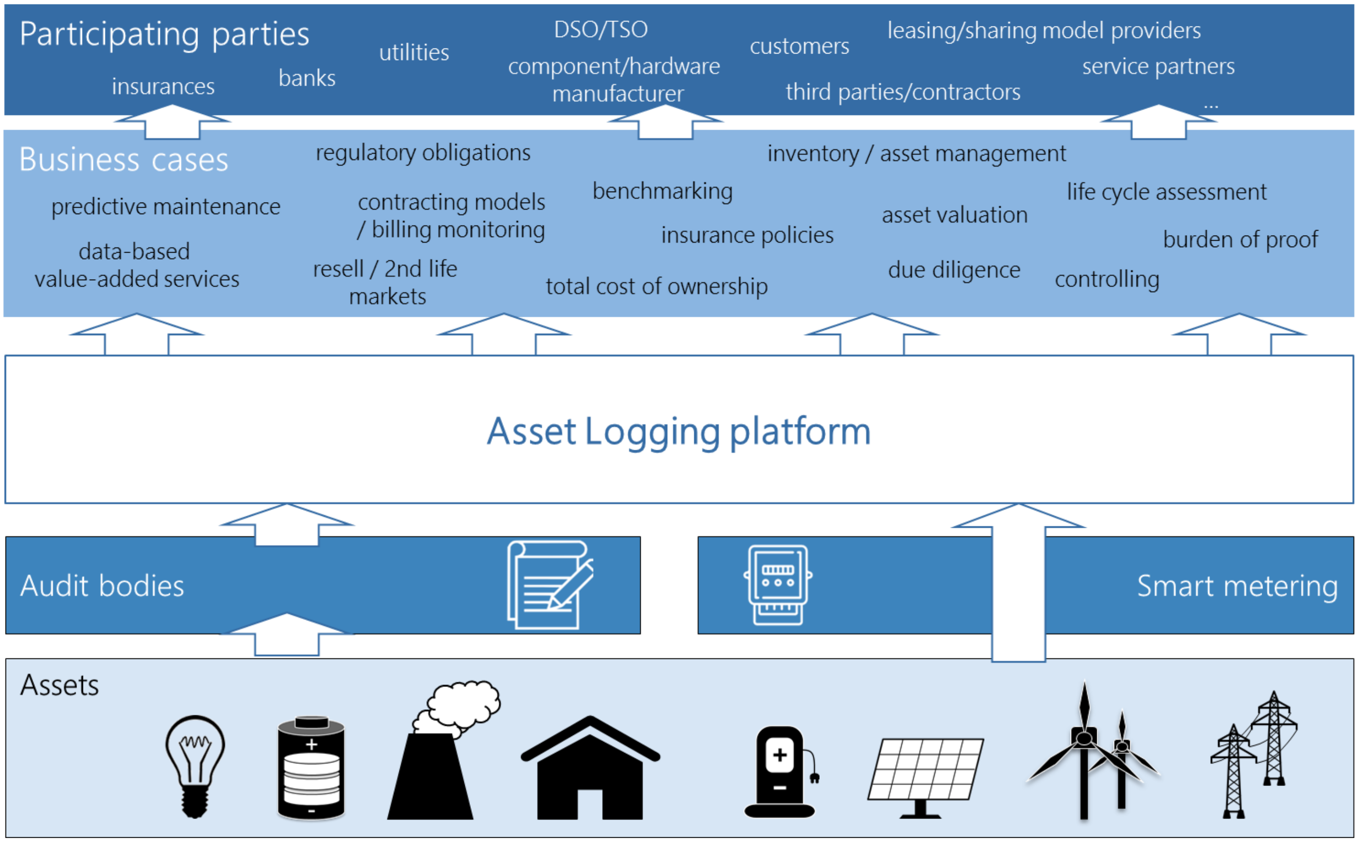

Figure 3: Schematic illustration of an Asset Logging platform

tamper-proof data basis, the information asymmetry can be eliminated and a comparable evaluation of supplier and buyer side is possible. Especially within the energy sector, technical due diligence plays an important role. All information on utilization and operation that is included in the assessment is therefore particularly relevant. Within the increasing relevance of leasing and contracting models, a common database is of particular interest not only for billing purposes, but also with regard to proof of performance or efficiency. Furthermore, technical risk management as well as maintenance strategies and methods can be derived from this.

2) Blockchain-based platform concept

There are hardly any standardized processes regarding asset documentation. This gap could be filled by a platform with a comprehensive collection, maintenance and provision of uniform data records. Processes that are linked to data exchange can therefore potentially be stored in a decentralized, tamper-proof and traceable data repository (cf. [5]).

The basic structure of such a platform includes a selection of possible assets and the path of the data to the distributed data storage via auditing bodies, i.e. service providers or a trusted "(smart) metering system" on the one hand. On the other hand, applications or business cases can be set upon the provided data by the companies involved (see Fig. 3).

The described use cases in the field of asset logging have specific requirements regarding the characteristics of the underlying software platform, which are necessary to provide a reliable data basis. A suitable structure and architecture for this platform can subsequently be deduced from these characteristics and features. The platform has to fulfill four essential properties:

- Time-discrete data storage: The chronological order of events and measurements has to be represented reliably in the stored data.
- Immutability: Subsequent changes to or manipulation of stored data has to be prevented by the system.
- Transparency: All authorized stakeholders have access to their relevant data.
- Multiple write access: Decentralized data acquisition allows concurrent storage of multiple measurements or other data sets.

The identified requirements can be fulfilled by developing an appropriate data management infrastructure based on blockchain technology [2]. This technology evinces several distinctive features, which correspond to the demanded properties, and therefore, allows implementing a platform for decentralized data acquisition, immutable storage as well as automated and transparent evaluation. The overall concept is schematically depicted in Fig. 4.

Data from several sources is collected, digitized and hashed if necessary and subsequently written to the blockchain-based data platform. The decentralized structure

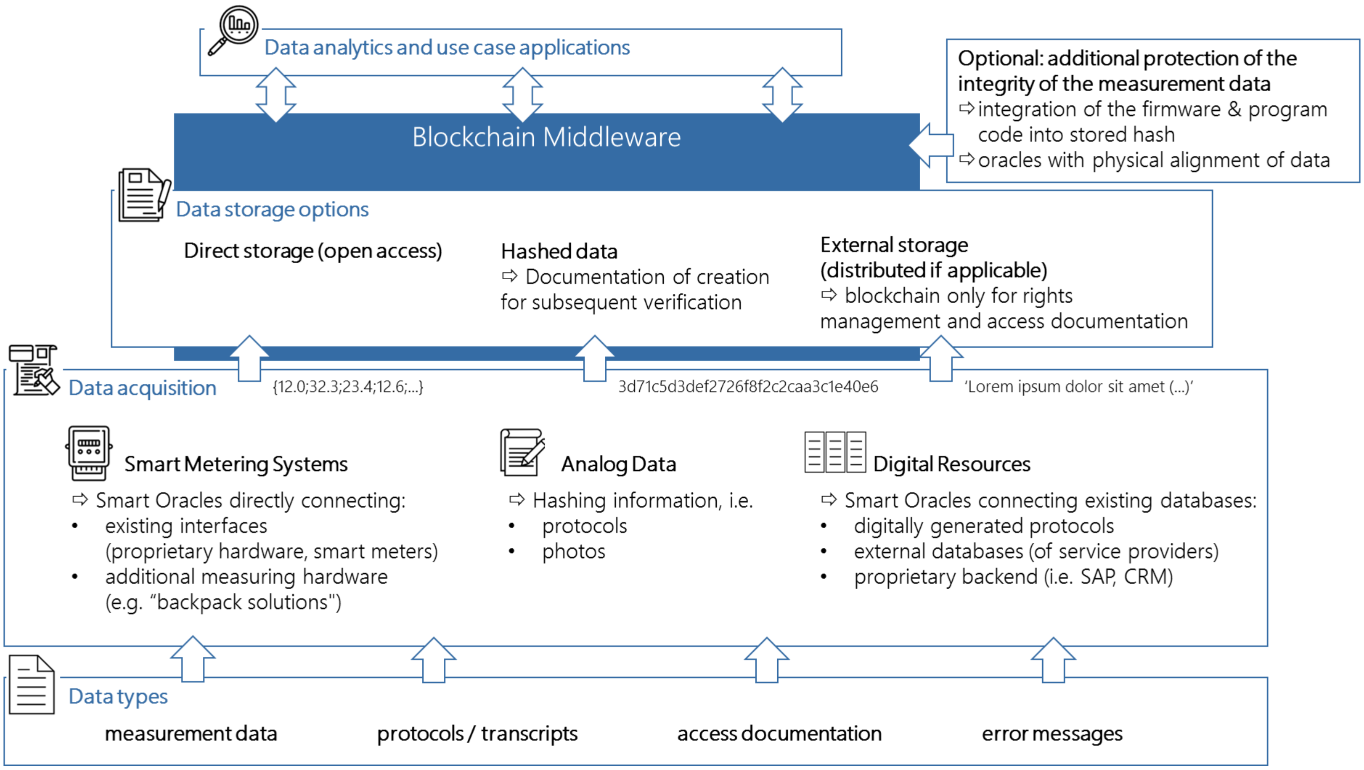

Figure 4: Technical concept of a blockchain-based Asset Logging platform

enables all stakeholders to directly access the platform and to reliably verify the data integrity. Smart contracts on the blockchain platform automatically verify, analyze and evaluate the data and therefore, provide the basis for use cases and applications which utilize this data basis.

3) Summary

The proposed Asset Logging platform offers the possibility to securely store documentation data and to provide relevant stakeholders with traceable and tamper-proof information. Nevertheless, there are several challenges yet to be addressed. Trustworthy data acquisition and transmission is the basis for trustworthy data management. A uniform definition of the interfaces (APIs) and the associated technological openness is decisive for the broadest possible application. Finally, the possibilities are by far not limited to energy applications; they apply to almost all industries with a high asset intensity. Ultimately, proof of a decentralized platform could develop into the industry standard in the future.

C. Supplier Switching

Currently, the supplier switching process of retail customers in the German energy market takes several days up to three weeks, since it involves numerous steps of data exchange, validation and confirmation between all affected market roles. Therefore, switching intervals lower than a month cannot be reasonably realized in the current system, leading to contract durations of at least one month, usually one year. This reduces the flexibility of retail customers to adapt to the market setting, since it is not possible to make use of potentially more economic offers. Moreover, this can also pose market entry barriers for new players, since only a very limited share of customers are able to switch in a given interval of time, increasing the required time for new players to accumulate a competitive customer base. Therefore, the current system potentially prevents increased competition in the electricity retail market.

These observations show that an automatized solution for the described processes might offer considerably shorter switching times, enabling the retail customer to choose the optimal supplier on a daily or sub-daily base. This is also in accordance with the EU's so-called *winter package*, which demands "improving the customer experience around day-to-day operations such as billing and switching". Therefore, the main goal here is to improve both the communication between market actors and the internal processes for validation and confirmation. This can be achieved by appropriate IT infrastructure, which serves as a communication backbone for the whole process and ensures data consistency. The process involves several parties with potentially conflicting interests, such as grid operators, metering point operators, consumers and suppliers.

Therefore, blockchain technology is identified as a possible solution for this application [1]. Potential benefits are distributed data, the immanent validation mechanism and the low barriers for participation in the system. A proof of concept shows the general approach and allows evaluating these benefits, as well as a comparison to alternative implementations such as traditional databases.

1) Current Situation

The process for switching of energy suppliers in Germany is defined in a framework document called *GPKE*

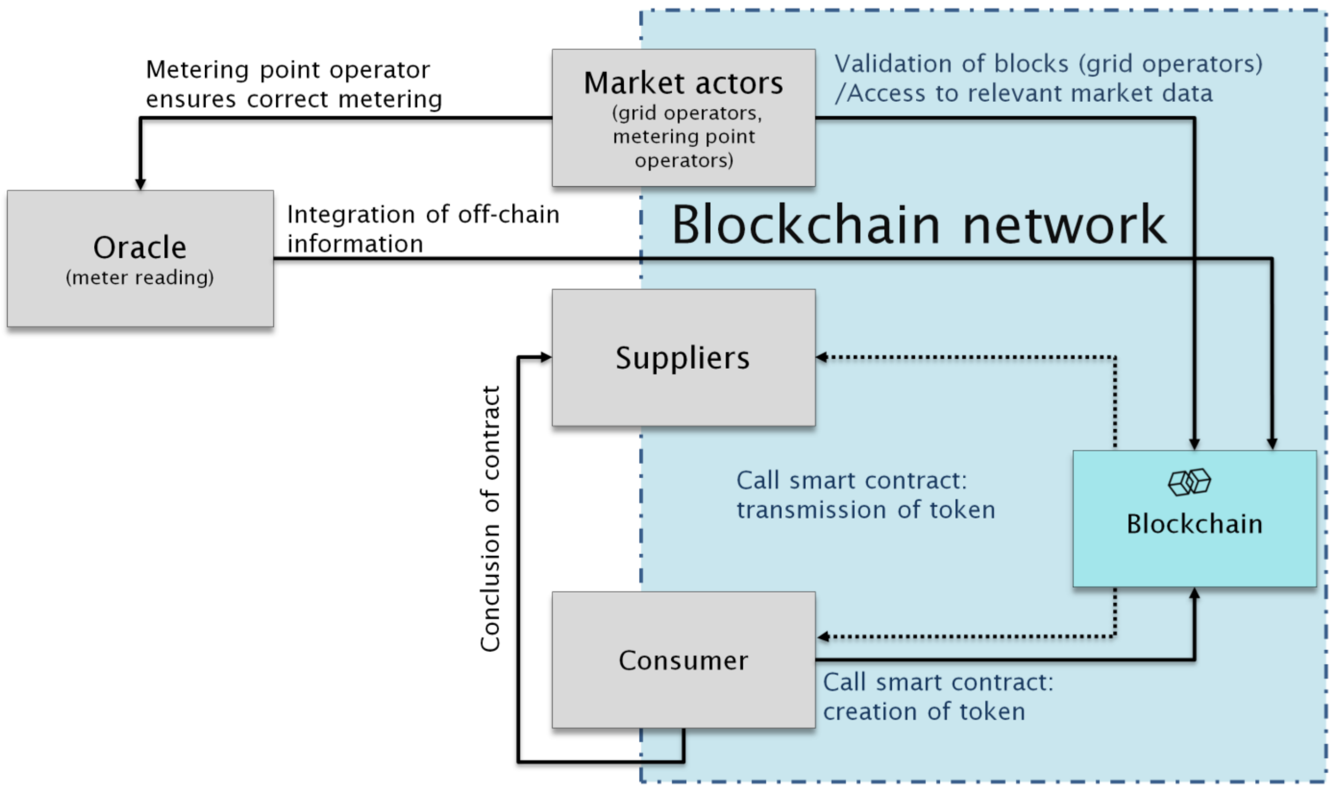

Figure 5: Schematic representation of a token-based implementation

("Geschäftsprozesse für die Kundenbelieferung mit Energie"). These consist of eight steps, which specify conclusion of contract, data transmission, validation and confirmation between the involved parties: current supplier, new supplier, distribution system operator, metering point operator and retail consumer. Data is mainly routed through the distribution system operator, which potentially causes inefficient processing. Moreover, several steps require manually checking the consistency and validity of transmitted data (e. g. customer details), which also affects the duration of the whole process negatively.

Due to liberalization of the energy market, about 1 400 suppliers offer electrical energy to retail customers in Germany. These are connected to almost 900 different distribution system operators. Although there are standardized formats and procedures for market communication, the variety of these market participants leads to additional problems in the communication, since the individual level of implementation of these standards differs vastly. Therefore, additional manual interaction is required in order to correct erroneous data.

2) Concepts for blockchain-based implementation

A blockchain as a special type of distributed database offers some key features to the user. These include immutability, transparency, independence from central authorities and decentralized data storage [1]. In the use case discussed here, this has several advantages for all participating parties: the validity of customer details and of the assignment of customers to suppliers can be checked and ensured at any given time, the distribution system operator as intermediate party for data exchange can be skipped in order to achieve more efficient communication, and also the communication between retail customer and supplier can be included in the system.

Automation is sometimes also quoted as a distinctive feature of blockchain platforms, but alternative implementations based on conventional IT architecture can provide this as well. Nevertheless, the potential benefits of a blockchain-based system justify closer examination in order to analyze different options of implementation, its performance and its applicability in the energy market.

Two different concepts for this system are presented. The first one, illustrated in Fig. 5, is based on *tokens* on the blockchain, which represent the right to supply a certain customer with electrical energy. For this, the concept of non-fungible tokens, which is available on the Ethereum platform, is applied [17]. These tokens are uniquely created and carry additional metadata, in this case e. g. metering point id, distribution system operator, end of contract and notice period. A smart contract enables the customer to retrieve and destroy the token in order to switch suppliers. This can be extended to only allow switching after payment has been registered. In this case, an oracle is applied to integrate the metered consumption in order to determine the amount payable. Alternatively, the payment can be processed on-chain via a different class of tokens, similar to cryptocurrencies. All involved grid operators continuously validate the data as new blocks are written, ensuring consistent data for all participants. Therefore, the appropriate consensus algorithm for this application is proof

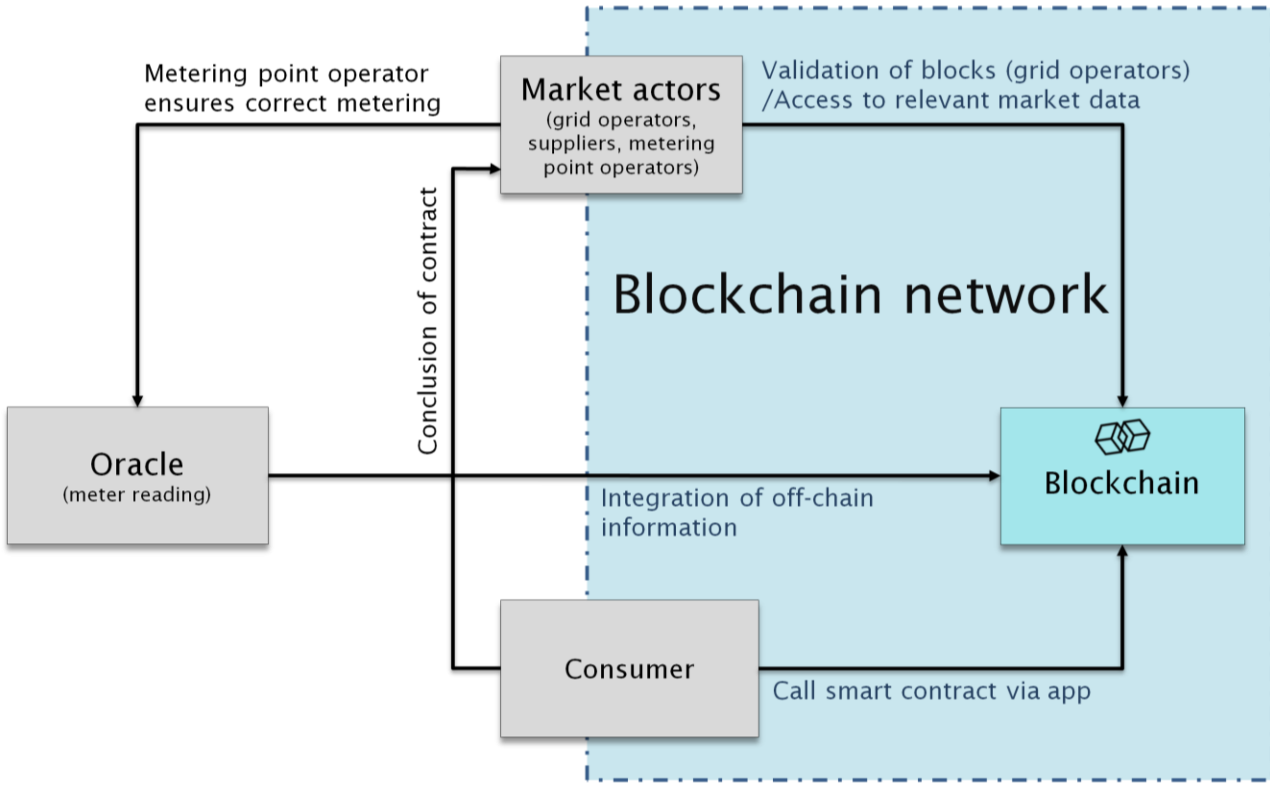

Figure 6: Schematic representation of a mapping-based implementation

of authority, which avoids the common disadvantages of proof-of-work-based blockchain systems, such as high computational effort and high energy consumption.

This approach has the advantage of being intuitive given that the currently most widespread applications of blockchain are cryptocurrencies, which mainly require tokens to be transferred. Nevertheless, it is quite complex to implement and rather inflexible for further extensions regarding related use cases.

The second concept, schematically depicted in Fig. 6, utilizes the *mapping* feature of the Ethereum blockchain platform. This allows assigning additional data to public addresses of the blockchain system, thus avoiding the complex process of creating, transmitting and destroying tokens for every switching process. As for the previously described concept, these data include information about the consumer such as metering point id, contract details and distribution system operator details. Additionally, the current supplier is stored here, since this assignment is not represented by token ownership.

The actual switching process is based on a smart contract, which is called by the customer and assigns new data to his address. Within the smart contract, accordance to contractual conditions and consistency of the data is ensured. Due to the immanent validation by involved grid operators, the resulting data is guaranteed to be correct. This concept can also be implemented as a proof-of-authority blockchain. All relevant market actors can access and read the full state of the system at any given time; therefore, the assignment of consumers to suppliers is sufficiently represented by this approach.

This concept can also be extended to include payment via an analogous approach as described before. In this case, the smart contract which is invoked for switching also checks the correctly processed payment.

The implementation of a proof of concept on the Ethereum platform shows that this approach can be realized with comparably low effort. The test environment allows examining proper functionality, as well as sufficiently low processing time below the currently applied metering interval of 15 minutes.

3) *Further Applications*

A comprehensive implementation and application of the switching process as described in the second (mapping-based) approach has the additional advantage of being easily extendable in order to include additional features and therefore, to utilize the established communication infrastructure for further use cases. The possibility to change the assigned supplier at a given location allows introducing a roaming functionality, enabling consumers to also use their preferred supplier when away from home by switching the supplier of their current location and returning to the default value afterwards. This can prove useful for applications such as charging an electric vehicle at public charging stations or for settlement of electricity consumption at holiday homes.

4) *Summary*

The analyses demonstrate potential for improvement in the current processes of switching suppliers in Germany. Two concepts show that a blockchain-based approach is a possible solution to this, but also evinces some drawbacks when compared to conventional databases. The main temporal advantage is expected to be caused simply by automation of the whole process, which does not necessarily require a blockchain to be achieved. Moreover, alternative approaches might be cheaper in terms of hardware, computational power and storage requirements.

Nevertheless, an exemplary implementation of a proof of concept on the Ethereum platform shows that the general concept is feasible. In order to reliably assess and compare the approach to a centralized one, the implementation of both options and the application to real-world demands is necessary.

Implementation of the described system and the corresponding regulatory adjustments are expected to reduce market entry barriers for suppliers, leading to increased competition in the market. Also the possibility to switch suppliers in intervals down to 15 minutes and even less increases price pressure on the supply side. This in turn can cause a countermovement on the long run, since smaller suppliers might not be able to cope with reduced profit margins, decreasing the overall number of suppliers in the market again.

D. Verification of Provision of Control Reserve

There exist two possible applications for the blockchain technology related to control reserve provision: verification of provision when marketing control reserve and during the pre-qualification procedure.

Primary, secondary and tertiary control reserve are tendered via regelleistung.net – the joint platform of the four German transmission system operators (TSO). There, providers place their bids consisting of offered power, power price and, in the case of secondary and tertiary control reserve, the energy price. Contracted bids are directly compensated via the power price, regardless of whether they are activated or not. In the case of secondary and tertiary control reserve, suppliers additionally receive compensation when activated by the TSO. The compensation is calculated by activated energy and the corresponding energy price. For this purpose, suppliers must verify the proper provision of the requested control reserve. Here, applying the blockchain technology could lead to efficiency gains. Currently, the planned operating point without provision of control reserve – the so-called baseline – and the actually measured operating point resulting from the activation of control reserve – the so-called active power – are compared in order to verify proper provision. The time series of these two operating points are recorded in operating protocols and must be stored for at least two months. If the contracted control reserve is not activated, these time series should not differ significantly. Primary control reserve is activated decentrally depending on grid frequency. In this case, verification is based on the time series of grid frequency and active power [18], [19], [20].

For all types of control reserve, supplier and TSO stipulate which data hast to be reported as well as corresponding lead time and temporal resolution. According to the transmission code [20], the provision of control reserve must only be verified upon request by providing the corresponding operating protocols. The baseline usually is determined via the method "anticipatory operating point". The planned operating point without activation of control reserve is reported with a lead time of five minutes and a time resolution of one second (one minute for tertiary control reserve). The active power must always be transmitted in real time. The difference between active power and baseline yields the activated control reserve [21]. Active power is measured, however, the definition of the baseline could be improved by setting up a blockchain solution. In addition, verification, i.e. the comparison of baseline and active power, (the comparison of grid frequency and active power in the case of primary control reserve) could be automated in order to reduce the TSO's effort.

The possibility to compare baseline and active power via a blockchain yields another use case – verifying proper provision during the pre-qualification procedure. In this procedure, potential providers of control reserve must prove that they meet the defined requirements. Although these requirements differ between the three types of control reserve, they always include an operational run during which the proper provision of the control reserve is verified and the pre-qualified power is determined. The supplier logs the operational run and submits the protocol to the TSO. The TSO then evaluates the protocol and verifies proper provision. In general, the operational run is performed by the provider himself and without participation of the TSO. However, the TSO can request to attend the operational run in case of poor quality or suspicion of manipulation. In the future, pre-qualification will only be valid for five years. The TSO then decides whether another operational run is required or data on past activations is sufficient [19], [20].

Suppliers can be pre-qualified at any time. Typically, the procedure takes at least two months [18]. Although the pre-qualification procedure itself is free of charge, the delay of two months may result in lost revenues since the prequalified power cannot be marketed yet. In order to accelerate the pre-qualification procedure, the PQ portal (https://pq-portal.energy/) has been set up. Here, potential providers can upload the required time series of baseline and active power which are then verified by the system. In principle, the blockchain technology could be used to store baseline and active power in a manipulation-proof way and thus, accelerate verification during the operational run.

1) Technical Concept

In both use cases, the comparison of baseline (grid frequency in the case of primary control reserve) and active power could be performed in a blockchain. Hence, the provision of control reserve could be verified by automatically comparing the two corresponding time series. Comparison with the main features of a blockchain-based system described above yields the following: In both use cases, no intermediary is involved. One may argue that the TSO acts as intermediary since he is responsible for verifying the proper provision of control reserve. However, he is also directly involved as customer, and therefore ultimately not regarded as intermediary. But, most of the other features apply to the use case. Thus, applying the blockchain technology appears to be appropriate. The corresponding setup is described in the following.

In the case of secondary and tertiary control reserve, baseline and active power are transmitted to the blockchain instead of to the TSO. The TSO still decides which suppliers are activated and submits the result of his decision to the blockchain. The proper provision of control reserve is then automatically verified and the amount of control energy is determined. Then, the TSO calculates the corresponding remuneration. The last step could additionally be integrated into the blockchain via smart contracts. In the case of primary control reserve, grid frequency and active power are transmitted to the blockchain in order to realize the automatic verification. The decision which suppliers are activated remains unchanged; it is still dependent on grid frequency. In the case of a pool, data transfer is still realized between the aggregator and the TSO or the blockchain, respectively. The described blockchain solution does not aim at opening the market for the direct participation of small suppliers.

Implementing a blockchain solution creates another advantage. As explained above, the TSO assumes two roles – customer for control reserve and verifier of proper provision. The blockchain solution allows a clear separation between these two roles. The verification is realized via the blockchain, and thus, the TSO only acts as customer.

The blockchain's essential functionality is the comparison of baseline (grid frequency in the case of primary control reserve) and active power. The supplier transmits the corresponding time series to the blockchain via smart contract oracles, which connect the blockchain to the outside world. Additionally, information on activated suppliers is required. For this purpose, a time series for each supplier and type of control reserve is generated. The default value is zero for all points in time. In case of activation, the power to be activated in MW is entered for the relevant points in time. The temporal resolution of this time series must match the resolution of baseline and active power. When control reserve is activated, baseline and active power are compared and the TSO receives information on provision quality. If a supplier is part of a pool, communication is still realized directly between aggregator and TSO or blockchain, respectively. The required time series – baseline, active power and activation – are also aggregated at pool level. In the case of primary control reserve, suppliers transmit grid frequency and active power to the blockchain. In this case, an activation time series is not necessary as the required control reserve is activated decentrally and not by the TSO. If the frequency of 50 Hz is exceeded or drops by more than 0.02 %, the provision of control reserve is verified in the blockchain based on the time series of active power.

A consortium blockchain is most suitable for the described setup. This is a special type of private blockchain. It is also not publicly accessible, however, the validation of transactions is not limited to selected participants only [22]. A separate system is to be set up for the each type of control reserve. For the first use case – verification of control reserve provision – the group of participants is limited to TSOs and pre-qualified suppliers for each type of control reserve. All participants are entitled for validation. For the second use case – verification of the operational run during the pre-qualification procedure – participation is limited to suppliers intending to be pre-qualified. This can be realized e.g. by submitting relevant documents required for pre-qualification as precondition.

2) Evaluation

The application of the blockchain technology does not create new business models or markets in the context of control reserve. Demand for control reserve still results from system requirements and provisions of the Transmission Code [20]. On the supply side, no significant influence is expected either as long as pre-qualification conditions are not fundamentally changed – e.g. the minimum lot size would be reduced. The blockchain technology mainly creates possibilities for process optimization. The automated comparison of baseline (grid frequency) and active power allows decreasing the TSO's effort and cost. It is not possible to exactly quantify these savings though. Nevertheless, a rough estimation can be derived from the number of activations and the amount of suppliers. Primary and secondary control reserve are activated almost permanently. Tertiary control reserve is activated several thousand times per year, approx. 5,300 in 2016 [23]. Currently, 49 providers are prequalified for at least one type of control reserve [24].

In the future, the described blockchain solution could also be implemented in regional flexibility markets. Typically, a large number of small flexibility options will participate there. Consequently, the number of activations and thus, grid operators' effort associated with the verification of proper provision will increase. If blockchain solutions are also implemented in these cases, the potential will be significantly larger.

Ultimately, it must be taken into account that in both cases the described process automation would also be possible without the blockchain technology. The decision in favor of a system with or without blockchain essentially depends on respective implementation costs.

E. Peer-to-Peer Trading

The increase of decentralized renewable energy systems also leads to increased desire of many to sell and procure locally produced energy directly among peers. Due to the renewable energy act (Erneuerbare-Energien-Gesetz) and the derived subsidies for renewables that are guaranteed for 20 years, this strive for more independency is yet on hold. With subsidies expiring for renewables in the beginning of the 2020s, demand for regionally produced and traded energy is expected to be rising. Blockchain technology as a means of conducting micro-transactions might be the key to not only grant the possibility to trade energy on a peer-to-peer level, but fuels to idea of complete independence of established energy companies. The relevant regulatory framework, potentials and possible implementations of peer-to-peer trading is discussed in the following.

1) Regulatory Framework

Energy systems evolved during time of electrification around major power plants and electricity consumers with a high demand. Only afterwards, private households received a connection to the grid. In 1996, the EU liberalized markets and enabled the free trade of energy as well as the unbundling of sales and grids. With this came the emerging of new markets, new players and new forms of products and services. The development of peer-to-peer trading might be the next big step in the evolution of the energy system. Yet as was the case 1996 with the liberalization, the current regulatory framework was not designed for the emerging of independent, small-scale trade. Therefore regulatory frameworks evince a significant amount of obstacles that have to be overcome in order to make peer-to-peer trading possible.

Firstly, the harmonized European roles of market-communication as well as national laws do not distinguish small-scale market participants from large-scale traders like multi-national utilities. Hence, a wide variety of regulations has to be adhered to by every single prosumer in order to be able to trade self-produced energy to peers. These regulations include the provision and settling of taxes, reporting obligations to the authorities, the naming of a balance responsible party as well as the reporting of forecasts of demand and supply to transmission system operators. Secondly, national subsidies such as the German renewable energy act prohibit double sales of subsidized energy. Due to most renewable energy sources in Germany utilising these subsidies for the first 20 years of their operation, only a handful of plants are actually available for peer-to-peer trading today.

Overall, peer-to-peer trading theoretically is an option and legally possible. With high regulatory obstacles, missing simplifications for small-scale market participants (prosumers) and the high efforts for bureaucracy, the mass adoption of peer-to-peer trading seems unlikely, yet opens the possibility for utilities to serve as an intermediary for regulatory demand and bureaucracy.

2) Use Cases

The configuration of peer-to-peer trading comes in different forms and shapes. The following chapter briefly describes different configurations and their specifics.

- **Short-term markets:** alike existing markets, locally produced energy can be tendered on peer-to-peer markets with different multiunit auction mechanisms with a relatively high frequency (i.e. 15 minutes) providing only short-term supply (shortly before service provision). Auction mechanisms include different forms of uniform price auctions or pay-as-bid-auctions. In order to include small-scale prosumers and consumers, these mechanisms have to be automated and optimized to reduce complexity, risks and effort. Due to its high auction frequency, the risk for over-/undersupply is minimized.
- **Long-term markets:** compared to short-term markets, long-term markets have a reduced auction frequency, resulting in long-term contracts between demand and supply, reducing complexity and price volatility. Yet, these markets have a higher risk of supply or demand shortages creating the need for mechanisms to deal with missing or excess energy.
- **PPA:** a special use case of peer-to-peer trading are power purchase agreements. PPAs are long-term contracts between demand and supply with a fixed price to reduce the risk of price volatility on markets. PPAs nowadays are usually not traded on markets yet could be implemented on peer-to-peer long-term markets.

Overall, the market design, grade of automation, size of the market, participants and integration into current markets to avoid market abuse and gaming have to be thoroughly tested and simulated.

3) Potentials

With the subsidies enacted in the year 2000 and installation-rates of renewables rising in the following years, peaking in 2010, the amount of EEG-plants dropping out of subsidies will rise from 2020 with a peak in 2030 to 2035. Therefore, the amount of potential market participants is expected to be significant.

With the identified need for regulatory adjustments and the necessary research regarding market design and related issues, large-scale research projects, working groups and field tests are required to address open questions.

Taking into account the German household electricity price components, it becomes clear that the costs of trade, sales, production and respective margins at the household electricity price in total only account for 6.42 ct/kWh (in April 2017) [23]. After deducting the average day-ahead price of 28.87 €/MWh (April 2017) for energy procurement, this results in sales and margin shares of approximately 3.53 ct/kWh. Based on the average household electricity price of 29.86 ct/kW, this corresponds to 11.8 %. Under the assumption of reducing this cost to a minimum by substitution of the intermediary (i.e. the utility) by blockchain technology, this is the theoretical potential for households. Considering the bureaucracy and expenses due to current laws and regulations, this margin is expected to be lower. This shows that without reducing the amount of bureaucracy, peer-to-peer trading is rather of informational interest in form of a value-added service, changing the role of the utility from a supplier of energy to a service provider (“bureaucracy-as-a-service”) without significant financial benefits for peer-to-peer traders.

4) Value of Blockchain Technology

The blockchain technology is only valuable as a platform for many users and many different use cases. Thus, the value within the use case of peer-to-peer trading comes in to place as a common standard to process transaction among peers without a centralized intermediary. Unlike utilities serving as a trusted intermediary – as they do in services that already reached market maturity – the blockchain serves as a trusted, tamper-resistant level playing field with a very high availability and security among different players. In case of regulatory adjustments, the blockchain could in the end even substitute existing intermediaries.

In reality, due to the administrative tasks and duties, service providers will always be necessary to a certain extent. The blockchain in this case allows for individual products on the front-end-side while in the backend, the blockchain serves as a standardized platform for transactions. Another value is created for customers by not being tied to a single product or service provider due to a common infrastructure for business transactions, thus creating more choice leading to more competition. Another advantage of a common blockchain platform is the utilization of synergies. Instead of developing or procuring individual software solutions, service providers only have to focus on individual branding of the front-end.

Another example for the value of Blockchain is the reduction of transactional costs. According to German tax laws (§ 9 StromStG), energy that is produced and consumed within 4.5 km by power plants < 2 MW are free of electricity tax. While this requires vast bureaucratic efforts to prove to the authorities for a single contract, blockchain technology can enable tamperproof records of all transactions taking place within 4.5 km of range and can collectively be monitored in real time by the tax authorities.

V. CONCLUSIONS AND OUTLOOK

This-study shows that blockchain technology builds on a variety of existing technological building blocks - such as digital signatures, asymmetric cryptography and hashing - to create a distributed database structure. The core innovation of the blockchain is the so-called consensus mechanism, with the help of which agreement can be reached on past changes in the database (i.e. transactions). This makes it possible to create trust decentrally and without intermediaries and guarantees a very high degree of security. The blockchain is extended by so-called smart contracts to become a blockchain platform on which programs can be executed automatically and, for example, business processes can be mapped, optimized and automated. These features enable use in many areas and industries - including the energy industry. The selected clusters of use cases which appeared to be most promising for closer examination and practical implementation show that all of them use the underlying blockchain system as communication infrastructure or data exchange platform. Moreover, they partially depend on the same data, leading to the conclusion that synergy effects of a platform designed for a variety of use cases could potentially make the system viable.

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