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Blockchain energy: Blockchain in future energy systems☆,☆☆

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A B S T R A C T

The ongoing, in-depth transformation of the electricity sector towards increased use of alternative, renewable energy sources extends beyond a simple decentralisation drive in the electricity market. The transformation process is characterised by the interplay of old and new technologies from the energy sector as well as structural coupling with other sectors, such as the information and communications technology (ICT), enabling the technology transfer as well as market entry by information technology (IT) actors. Blockchain-based technologies have the potential to play a key role in this transition by offering decentralised interfaces and systems as well as an alternative approach to the current organisation form of the energy market. This paper discusses the applicability and prospects for blockchain-based technologies in the energy sector, which are described using the term "blockchain energy". For the purposes of this study, blockchain energy encompasses all socio-technical and organisational configurations in the energy sector based on the utilisation of the blockchain principle for energy trading, information storage, and/or increased transparency of energy flows and energy services. In the following chapters, the authors present and discuss the current transformation in the electricity market, followed by a review of the different utilisation possibilities for blockchain technologies in the energy sector and a discussion of the barriers and potential for blockchain energy using a transition studies perspective. Finally, the opportunities and risks of blockchain energy are discussed.

1. Energy market transition

The last decade of the 20th century already showed signs of a turnaround in the energy sector in Germany. On 1st January 1991, for example, the German Electricity Feed Act came into force with the aim of granting a remunerated purchase of electricity generated from renewable resources (water, wind, sun, etc.). Renewable Energy Sources Act followed in 2000 and was continuously adapted. However, it was not until the nuclear accident at Fukushima in Japan in the spring of 2011 that the energy sector made the decisive breakthrough, particularly through a rethink in the policy. The climate change, Fukushima, a growing awareness of energy issues in large parts of the world, coupled with the broad and cost-effective availability of sensors, the information and communications technology (ICT), and technologies for the use of renewable energy sources, led to a sustainable change in the relationship between energy and society [1].

The political decision to turn energy systems around has led to major challenges from a political and social point of view as well as

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from a technical and transformational point of view. This has had a correspondingly strong influence on the energy market. Progress and technological developments in the areas of networks and sensors, as well as ICT, gave the energy system transformation a further boost. The change in the energy market is thus characterised not only by political boundaries (liberalisation and deregulation) but also by so-called digitalisation. The change in the electricity market as the most important area in the energy market is characterised by the further development of the classic electricity grid into the so-called smart grid and by the efficient possibilities for decentralised energy generation. This, in turn, opens the door to new structures, relations, and models possible such as energy prosumers, energy communities, crowd energy, electricity trading at various levels, etc.

1.1. Grid

The power grid is an electrical network consisting of electrical cables, switch gears, and transformers, as well as the connected generators and consumers. The main feature is the unidirectional flow of energy over long distances. To reduce losses, transport is generally carried out at different voltage levels, e.g. extra-high voltage (380 kV/220 kV, transmission network), high voltage (110 kV, supra-regional distribution networks), medium voltage (10 kV–30 kV, regional distribution networks), and low voltage (0.4 kV, local distribution networks). These network levels are connected by transformer levels.

The grid is designed to transport electrical energy reliably and economically, thus ensuring supply reliability. The physical principle of the balance between consumption and production is essential, as the power grid structure has virtually no capacity for energy storage [2]. This is a constant challenge for grid operators. The principle of balance will continue to apply in the future, but intelligent control systems together with efficient storage technologies can support the provision of balancing energy and grid-stabilising measures.

In the light of the future national and global challenges of the 21st century, a transformation of current power grids is foreseeable, although different starting conditions are regarded as possible [3]: A supra-national or even global super-grid, which couples very large, centralised energy producers with large-scale transport grids; a decentralised and prosumer-oriented off-grid network in which energy transfers take place only locally or not at all, since the prosumers act as self-suppliers, and a decentralised, locally, and regionally connected smart grid system in which prosumers generate energy locally with the help of innovative communications, energy storage, and energy metering technologies and transport it based on demand forecasts.

1.2. Smart grid

Renewable energy sources are increasingly being integrated into the energy system, and measures to increase efficiency and reduce consumption are gaining acceptance and are regarded as the key to success in the energy system transformation. A smart grid implies decentralisation, as well as the consistent use of sensors and ICT. According to Ref. [4], a smart grid is defined as an electrical system that uses information, bidirectional, cyber-secure communications technologies and intelligent software applications across the entire spectrum of the energy system in an integral manner, from generation and storage to the end-points of electricity consumption. This development will transform the previously rigid value creation structures into dynamic value creation networks, and there will be a paradigm shift in energy supply from "to-you" to "with-you" [1,5]. It is important to understand that the transition from the conventional power grid to the smart grid is not only technological innovation but goes hand in hand with an organisational-political and socio-economic change.

Digitisation and liberalisation are transforming the socio-technical system known as "electricity market" and are bringing numerous new transactions (not only in the economic sense but also in terms of events, control signals, generally digital data sets) among the actors and the subsystems. The prerequisite, of course, is the secure, efficient, and transparent execution of these transactions. The blockchain technology can make a significant contribution to this. Application scenarios are for instance:

- The provision of energy control and grid-stabilising measures;
- Electricity trading at the macro and meso levels as well as neighbourhood and tenant electricity models;
- Certification and proof of origin for renewable energy sources (type, location, and time of energy generation);
- Control of the energy consumption behaviour of networked intelligent devices (Internet of things) in real-time (load control);
- Automation of the billing process, including payment and/or remuneration of charges, fees, etc., also cross-sectoral;
- Transparent provision of reliable data from the energy sector, for example, consumption statistics or statistics on energy production from renewable sources (wind, solar, etc.);
- Asset management for distribution network operators and utilities.

The blockchain technology means distributed consensus-building directly between the actors (without additional intermediaries) and the mapping of values and rights (transparency of origin and ownership). It enables smart contracts, for example, for cooperation and performance accounting of autonomous systems, and it stands for traceability and irreversibility [6]. This disposition is the perfect, proactive basis for the expansion of the smart grid and thus for the interaction of the various players in the organisationally and spatially decentralised electricity market.

1.3. Decentralised power generation: prosumers and crowd energy

Generally, available technologies such as photovoltaic systems and home energy storage are the obvious features of decentralisation in the energy sector. The consumer of electrical energy can itself act as an energy producer and, if necessary, as a provider of storage capacity: The concept of the energy prosumer. An energy prosumer is an actor who produces, stores, and consumes his own energy, but also exchanges or trades any surpluses. This does not necessarily mean that the prosumer is self-sufficient. They are still integrated into the "public" electricity grid and can compensate for an energy deficit from the grid and, conversely, release an excess of self-produced energy into the grid. The strength of the concept becomes particularly clear when individual prosumers join together to form prosumer communities, i.e. a crowd. Crowd energy refers to the cooperation of prosumers and the bundling of their resources with the help of ICT [5].

Prosumers in a crowd primarily consume the energy they generated themselves and are actors in energy micro trading by trading surplus, but also needed energy with other prosumers of the crowd. The crowd energy concept is the perfect basis for blockchain applications or platforms. The concept presented by Ref. [5] can also be interpreted as a "decentralised autonomous organisation"—a decentralised network of autonomous agents, which is based on an optimal function [7]. This means that, for example, photovoltaic systems and storage facilities can carry out directly (peer-to-peer (P2P)) energy transactions with consumers present in the network (e.g. charging stations for e-mobility).

The blockchain technology is the ideal basis for any type of the crowd system: Smart contracts, traceability and proof of ownership (provenance), identity management (prosumers and machines), and small-volume transactions. The basic functionality of a blockchain platform in a crowd system is shown in Fig. 1 [8].

2. Blockchain applicability in energy sector

As mentioned at the beginning, the energy market and in particular the electricity market is in a transition phase, based on political-regulatory measures as well as technological developments. A large number of traders and processes with corresponding transactions characterise the decentralised electricity market. Security and reliability are central elements for the functioning of the market; this is classically ensured by the role of intermediaries. The applicability of the blockchain technology in the energy sector, therefore, dictates security and trust.

The blockchain technology allows for the creation of a distributed ledger (database as the distributed ledger). The main characteristic is the term distributed that the data are not only stored centrally, but simultaneously with all actors/nodes in the blockchain network, which means that the integrity of the data are not reliant only on one instance. However, this also means that all nodes must agree on the validity of the data or the blocks containing it. The process that ensures this is called consensus mechanism and is extraordinarily complex, which is based on comprehensible and verifiable rules. Blocks validated in this way are concatenated using a cryptographic Hash function. All actors in the blockchain network can view and track the blocks at any time, but cannot change them afterwards, thus ensuring the transparency in this ecosystem. An asymmetric cryptosystem is used in order to guarantee the integrity of the data and actors.

This, admittedly very abbreviated, description of the blockchain technology shows that it is possible to create a high degree of security against manipulation and facilitate trust between foreign actors (users) without the need for additional intermediaries. Furthermore, transparency without identity disclosure is guaranteed. Thus, this technology can be the basis for various applications in the energy sector. The assessment is further reinforced if another important feature is taken into account: The concept of a "computer-aided transaction protocol that executes the terms of a contract" [9], which is referred to as a smart contract. The program logic representing the smart contract is executed in the consensus network, whereby an agreement is reached on the result of the execution and stored in the blockchain [10]. External triggers (transactions, messages, and events) activate the execution of a smart contract. Like data, a program logic cannot be subsequently changed once it has been anchored in the blockchain. It should be noted that smart contracts are not contracts in the sense of civil law (at least in the European legal system).

In summary, it can be said that the blockchain technology uses the consensus mechanism in the network to create the agreement on transactions in the distributed database. Manipulation security, trust, and transparency are given without intermediaries. In addition, smart contracts offer enormous automation potential for business processes and procedures, such as those found in the energy industry, in particular, the P2P energy sector. However, the choice of model is crucial. This concerns the consensus mechanism as well as access to

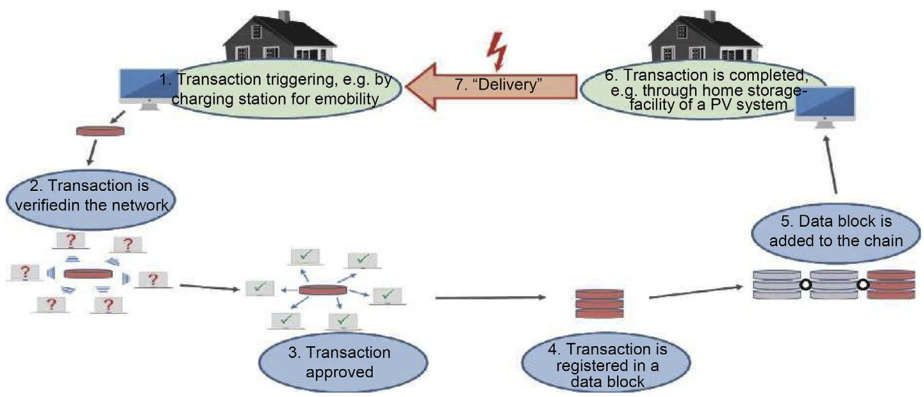

Fig. 1. Blockchain principle for crowd systems, adapted from Ref. [8].

the network (un-permissioned and permissioned) and access to the data (public and private) [11].

Public blockchains, which use proof-of-work as a consensus mechanism, are not acceptable for efficiency and environmental reasons (resource requirements) in the energy sector. Especially when processes and concepts such as distributed demand response (DR) management are considered, private blockchain networks that are started by a company, an organisation, or a consortium are an option. Access to the network is by invitation (permissioned) in order to ensure the quality of the participant structure, for example in terms of a possible service provision. This controls who can participate in the network, although the access mechanism can vary, e.g., existing participants could decide on future market participants or a regulatory authority could issue licenses for participation. In the work of [12], for example, distributed smart grid demand management based on the blockchain and smart contracts was discussed and validated using a simulation prototype on the Ethereum platform (cf. Fig. 2).

Both the characteristics of the blockchain technology and the availability of smart contracts on platforms such as Ethereum provide a positive answer to the question of applicability in the energy sector. The decentralisation of the energy market and corresponding P2P applications without intermediaries can be stimulated by this. The Munich Research Centre for Energy Economics has conducted a study on the potential of this technology in the energy sector with more than 160 energy experts from the operational and strategic fields [13]. The energy value chain was comprehensively analysed and over 90 applications of the blockchain technology were identified, which can be grouped into various categories (see Fig. 3).

These categories and use cases of the study by Ref. [13] largely coincide with the work of [14], developing a systematic overview of blockchain activities and initiatives in the energy sector. The study evaluates 140 blockchain research projects and start-ups and shows not only the distribution of use cases but also the distribution of platforms and consensus mechanisms (see Fig. 4).

As a conclusion from the studies by Refs. [13,14], it can be seen that the blockchain technology with smart contracts is suitable for applications, which are characterised by many actors with a common database. Smart contracts are necessary both for P2P trading and for many automation cases, which is why the Ethereum platform is widely used in the energy sector. The tamper-proof documentation and access to processes allow the automation and optimisation of processes between a multitude of actors. A prerequisite, however, is digitisation in the energy sector, i.e. the existence of smart meters, the use of sensors and ICT on the basis of corresponding broadband supply, and above all corresponding standardisation.

The overall societal attitude towards and assessment of possible blockchain-based development of the future energy system are also determined by the success or failure of pilot projects and the expertise of experts. For example, the German Energy Agency sees great potential in the blockchain technology on one hand for increasing the efficiency of existing energy processes and on the other for penetrating the energy market with digital applications. The integration of decentralised energy generation and P2P trading are the keywords [15]. This assessment is reflected worldwide in numerous (energy) projects with a focus on the blockchain technology. Reference [16] shows a selection of blockchain energy projects and presents case studies for the projects Brooklyn Microgrid (New York), White Gum Valley (Fremantle), and Quartierstrom (Walenstadt).

3. Blockchain energy in energy system transformations—transitions perspective and analysis

The global energy system is mainly based on a centralised paradigm—a small number of centralised producers are supplying electrical power to a large number of consumers using the established international, national, and regional infrastructure in the form of electricity transmission networks: The electricity grid [3]. Due to its decentralised, distributed nature, the blockchain concept and blockchain-based energy technologies do not readily fit within this paradigm. Compared with the proactive role of users in the blockchain, energy consumers in a centralised energy system have a passive role as energy recipients, further, the transfer of a commodity (energy) is monodirectional, as is the transfer of payments for the use of this commodity. However, global “wicked problems” such as overpopulation, climate issues, and questions of wealth distribution and democracy pose major challenges to future developments in energy systems, some of which cannot be effectively answered by their current configuration [17]. Therefore, energy

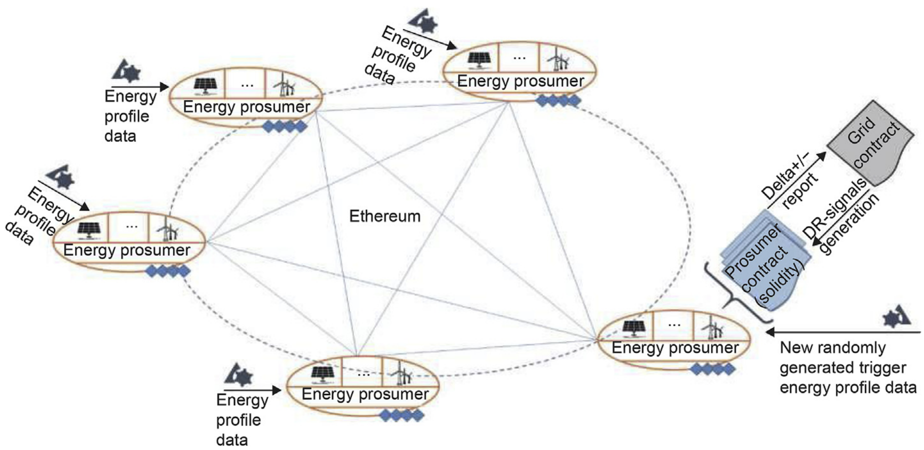

Fig. 2. Simulation model energy prosumers and DR management with blockchain and smart contracts, based on [12].

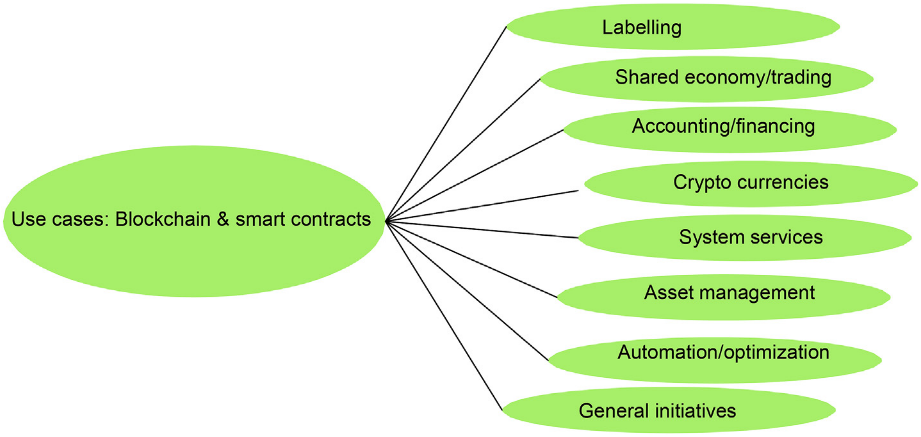

Fig. 3. Categories for applications of blockchain technology and smart contracts in the energy sector.

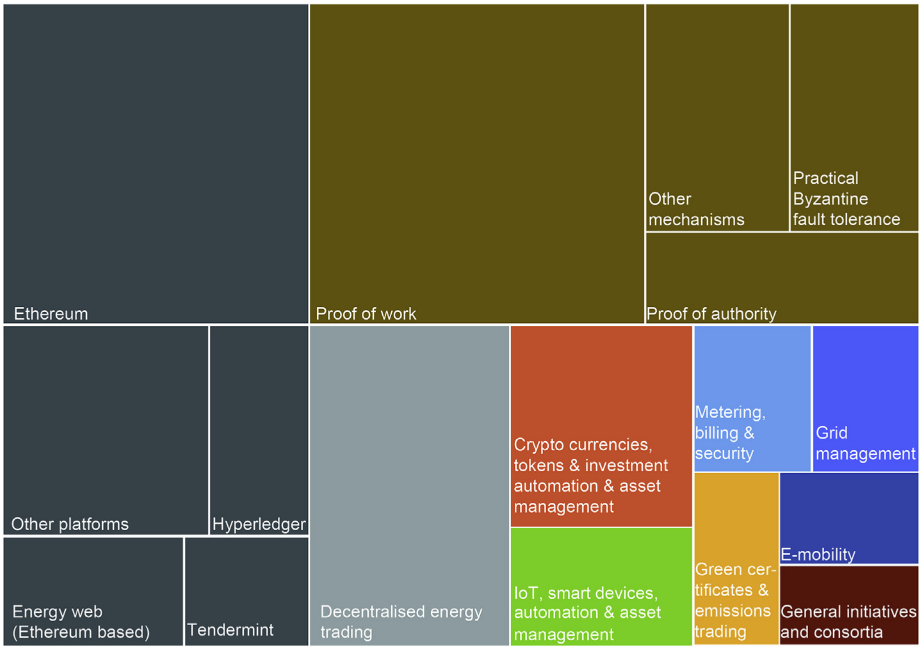

Fig. 4. Blockchain applications in the energy sector: Categorisation according to platforms used, consensus mechanisms used, and activities (based on [14]).

systems are increasingly pressured to transform in order to adapt to a changing environment [3]. These landscape pressures create the windows of opportunity [18] that may be used by proponents of blockchain-based energy systems in order to shape the blockchain into a core element of future energy systems.

The shape and characteristics of such a future system are, however, far from certain. In a recent study [3], has presented three potential future scenarios: Continued development of centralised energy networks towards continental or even intercontinental “super-grids”, intelligent and cross-sectoral smart grids tying the energy sector more closely to other parts of the economy or a largely distributed system of semi-autonomous and autonomous energy users, described as “no grid”. While the smart grid scenario offers the best opportunity for the development and diffusion of blockchain-based energy, the utilisation of the blockchain in small “neighbourhood grids” would also be possible in a “no-grid” future.

Energy system transitions and transformation processes have been observed at all levels, however, in line with the transitions theory [19,20], initial applications and experiments are mainly implemented at a local level [21] in the form of pilot projects, living labs, and other experimental settings and arenas [22,23]. Therefore, it is reasonable to expect that initial applications of blockchains in the energy sector will also take place at a local level using local contexts, an assumption that is supported by initial studies [21,24,25].

Even taking into account these initial developments, blockchain technologies in the energy sector can still be considered innovative newcomers, who are not part of incumbent energy regimes and therefore need to be developed in protected areas where there are at least partially protected from market selection mechanisms [25,26]. While regime actors in some of these cases support the development of these protected areas [25], on the whole regional, national, and global energy regimes generate a range of barriers, manifested through established industry structures, the dominance of certain technologies and supporting infrastructures, a knowledge base focused on established technologies, public policies, markets and user behaviour and the cultural role, and importance of existing systems [27]. In the following paragraphs, the authors will briefly summarise and discuss these barriers, focusing in particular on their effect on blockchain energy and potential approaches to overcoming them.

Both established industry structures and dominant technologies and infrastructures represent a barrier for blockchain energy technologies mainly due to them being developed for a centralised energy system both in terms of design and in terms of economies of scale. The latter issue is of particular importance when considering project support by major actors, such as the “Big Six” energy companies in the UK or the “Big Four” energy companies in Germany, who will often be unwilling or unable to invest in project below a certain size, mainly expressed in terms in power output. While energy projects developed out of grassroots initiatives do exist, they are often limited in size and scope [28] and may be hindered by existing legal frameworks [18,29]. One possibility for blockchain energy to surmount these barriers is through a sectoral coupling, with information technology (IT) companies using their existing knowledge on blockchains in order to enter the energy sector while using external support structures [21].

The existing knowledge base in the energy sector is mainly keyed towards the utilisation and optimisation of incumbent technologies within existing frameworks, creating issues for blockchain proponents due to both lacking technical knowledge and a lack of supportive legal frameworks [3]. While niche actors working with blockchain energy are gathering knowledge from local experiments and pilot projects, compounded by cross-sectoral knowledge transfers from IT and finance, the existing knowledge pool is still developing.

Political actors and policy can have both positive [26] and negative [18] effects on the development and diffusion of blockchain energy. Regarding the latter, the main challenge is often not an overt adversarial agency, but rather detrimental side effects caused by a political change [3,21]. On the other hand, the lack of existing policy frameworks makes the support from local or regional policymakers a crucial factor in the creation of initial proto-markets [26].

Potential blockchain energy users and markets exist in most global settings, ranging from post-industrial countries to developing regions, with different user profiles, requirements, and expectations. While in developed countries decentralisation of energy systems is supported as part of environmental, sustainability, and transparency drives, developing countries benefit from decentralised networks as a vehicle for the provision of electrical energy in off-grid areas. Concerning the state of the incumbent energy regime itself, it can be argued that a successful introduction of blockchain energy is most likely either in liberalised energy regimes [24] or in cases where the energy regime is either unstable or does not exist at all [30]. In the case of a strong, but not completely liberalised regime may represent a significant barrier, as small producers may be blocked from joining the electricity grid and therefore, from trading excess energy [29]. With regards to user behaviour, one main barrier may be the increased agency requirement for potential blockchain energy users compared with the more passive, “conventional” energy consumer role [17]. Solutions for the latter barrier may be found in partial or full automatisation of the underlying systems, where sectoral coupling with the IT sector may bring in actors with the necessary resources and knowledge [21].

Finally, the cultural significance of the existing regime does not represent a clear barrier, however, a public association of blockchains with cryptocurrencies may have a negative effect on the public perception of blockchain energy. In general terms, public expectations from any future energy system can be described using the energy trilemma concept: Energy security, energy equity, and energy sustainability [31]. While blockchain energy can be linked to energy security due to its increased resilience and the by-product of decentralised generation, and to energy sustainability through the use of renewable energy sources, energy equity could pose a challenge at early stages due to the lack of economic scale effects in early blockchain networks. However, a blockchain system in a later development stage may be able to fulfil the equity requirement, depending on its organisational structure and the utilised business model [17,32].

4. Opportunities and risks for blockchain in energy sector

The blockchain technology has become a mainstream topic of discussion; its disruptive nature has emboldened believers and further research. In the last several years, blockchain’s areas of applications have also diversified. The relevant technology has matured, and many new projects have emerged. Nevertheless, it is unclear whether blockchain’s impact on the various industries will be sustainable. The shaking up of the financial market has already illustrated how difficult it is to assess blockchain’s development and how many barriers will emerge over time. Previous pilot projects demonstrate that the use of the blockchain technology in the energy market can make sense, especially with regard to prosumers and microgrid applications. Despite the euphoria, this technique alone does not directly solve any of the existing problems. Cost-intensive infrastructure is a prerequisite for the operation of smart grids, particularly when it comes to integrating the prosumers, for instance. This means setting up a network with storage stations, solar or wind power plants, and smart meters, which must have access to a self-sufficient data network. In the following, the opportunities and challenges of a blockchain application are discussed in order to assess whether it is justifiable to use this technology in a smart grid.

4.1. Advantages

The general advantages of public blockchains are widely discussed in the literature. These are essentially the follows:

- The immutability of the data is (largely) guaranteed;
- High reliability and fault tolerance—everyone has the right to generate blocks and keep a copy of the data—an arbitrary attack on a few nodes will not damage the entire network;
- Data integrity—identical across all nodes on the network;
- Identity—each value can be assigned to a participant;
- No intermediary—thanks to smart contracts there is no need for intermediaries;
- Connectivity—new standards for data storage make it possible to combine functions from different providers;
- The technology provides prosumers with easy access to the energy market;
- Analysis—consumers can analyse and evaluate their power consumption more easily and qualitatively;
- The ongoing hype surrounding the blockchain technology is driving research around the decentralised energy market;
- Automation potential through smart contracts.

4.2. Disadvantages

While the blockchain has been somewhat successful on a small scale, several challenges must be mitigated before it can have a widespread impact on the energy sector. Aside from technical challenges that require solutions, legal and regulatory issues are currently the greatest obstacles for the widespread adoption of blockchain applications. These are questions concerning contract law, energy law, and data protection and sovereignty.

Although decentralisation can provide many benefits such as fraud prevention, faster transaction times, and no single point of failure, the traditional blockchain has the following weaknesses:

- Electricity costs—with the most commonly used consensus method proof-of-work, each transaction consumes computing power and thereby energy. The transition to more efficient consensus methods is challenging for public blockchains, although it can be expected to be realised in the next few years [33];
- Liability issues and consumer rights have not yet been clarified—all data are generally visible in public blockchains;
- Data protection, in particular within the framework of the European Union (EU) General Data Protection Regulation (GDPR), has not yet been clarified. All data are generally visible in public blockchains;
- The conventional energy network will be expanded to include the "insecure" IT component (keyword cyber-security). The blockchain is, for example, vulnerable to distributed-denial-of-service (DDoS) attacks;
- If attackers get 51% of the nodes of a blockchain, they are able to make changes (51% attacks);
- Scalability problem—a central technical problem is the challenge of scalability and performance. As the number of participants increases, the blockchain becomes sluggish. The challenge is to protect the integrity of the network through decentralisation while maintaining the speed of the network. The performance of a blockchain strongly depends on the degree of decentralisation (number of validators/miners and their geographical distribution). The more nodes added to a network, the more difficult it is to reach consensus. In a Bitcoin network, the block size is currently limited to 1 MB, and only one block is added every 10 min. As a result, there is a maximum of seven transactions per second [34];
- Changes to the code of a deployed blockchain usually require a large amount of effort. The majority of the network's nodes must approve a new version;
- The lack of standards for blockchain application programming interfaces (APIs) makes the interoperability of different technologies difficult;
- The problem of private key management—a user's identity is verified using a private key. If the private key is lost, it becomes impossible to gain access to the digital assets on the blockchain.

4.3. Risks

To make the blockchain applicable and feasible in the energy sector, it is crucial to lowering barriers for deploying the technology. The complexity, uncertainty, and lack of standards of the blockchain technology make the adoption difficult.

While the Bitcoin blockchain is considered to be secure, blockchains that allow the implementation of complex smart contracts have many vulnerabilities. For example, the best-known and most mature programmable blockchain Ethereum remains susceptible to countless attacks. Small programming errors in smart contracts can render them vulnerable to cyber-attacks.

If the P2P network fails, the security of supply is at risk. The decentralised nature of the network makes it almost impossible to determine who is responsible for errors in a public blockchain.

Various cryptographic algorithms are responsible for the security of the blockchain. Unknown vulnerabilities in the algorithms or their implementation cannot be excluded in the future.

Although it is unclear whether a powerful quantum computer that is capable of cracking state-of-the-art encryption will ever exist, such a computer may pose a threat if it materialises. From a data protection point of view, it might be unsafe to store encrypted data in a decentralised manner. After all, all participants in the network can temporarily store the data on their premises, and it may be easy to decrypt it over the course of many years. However, if this danger ever becomes reality, the blockchain will likely switch to quantum-safe cryptographic algorithms. The risk therefore only affects old data. That said, there are data that will still be confidential in 20 years, such as in the health sector.

The data are replicated across all nodes. The more nodes, the more redundancy there is, and the more disk space is used. While it might be favourable for digital currency such as Bitcoin to have as much safety as possible, it is questionable whether a platform for energy trading requires the same level of security as Bitcoin, which expends resources. Potential attackers can gain access to a complete copy of all data in the blockchain. Data analysis techniques such as data mining or correlation analysis can obtain information about users and blockchain applications [35]. However, concerning the privacy issue, the zero-knowledge proof method seems promising not only to transact safely among distrusted parties but also to remain private [36].

4.4. Opportunities

The blockchain is relatively young and immature. However, considerable potential benefits are already becoming apparent. The blockchain has numerous applications: Financial markets, P2P transactions, audit, healthcare, insurance, supply chain, voting, and so on. These applications provide insights into the seemingly unlimited possibilities of this disruptive technology.

One of the most important motives at the prosumer level that is in favour of using the blockchain is the independence from energy supply companies. While trading on a centralised platform can be easily manipulated, manipulation is more difficult and easier to identify on a decentralised blockchain.

There has been an emergence of solutions for connecting smart contracts with real-world data so that information from other infrastructures can be understood and used. This opens up new possibilities such as reducing the administrative overhead through having a direct connection with a payment provider.

Artificial intelligence (AI) could understand information from the outside world and translate it for smart contracts [37]. Integrating deep learning into the blockchain can solve data rights challenges and return the control of personal data to network participants [38]. In addition, data analysis can be used in conjunction with the blockchain to detect anomalies in data and identify suspicious activities. Consequently, it is plausible that AI will integrate with the blockchain into an autonomous, secure, and self-sufficient trading system. Furthermore, it could become a common practice for a fuel dispenser to negotiate prices and execute transactions autonomously with a nearby photovoltaic system in real-time.

The traceability of transactions enables solutions that make it possible to determine the source of energy. For example, if a smart grid is supplied with different types of energy, the consumer could choose to obtain energy only from photovoltaic sources. Therefore, the consumer would have more control and influence on the network if many consumers choose only certain types of energy (perhaps at a surcharge).

In a nutshell, the opportunities for prosumers offered by smart contracts lie in the cost reduction through process automation and the elimination of intermediaries. Such opportunities also result from prosumers taking an active role in the system without having to rely on an energy giant.

4.5. Private blockchains

A decentralised large-scale electricity market on a public blockchain is currently not feasible. The use of a private or permissioned blockchain, on the other hand, can address many of the problems of a traditional blockchain:

- There are no miners who want to profit financially from the network. As a consequence, the transaction costs are eliminated or negligible. In addition, network performance is improved, and the energy consumption is greatly reduced;
- When network access is restricted to identifiable participants, and there is the possibility of having central responsible authority points in the network, private blockchain systems offer increased data protection. In the case of private and public blockchains, anonymisation of the data is also a possibility [39].

However, in a private blockchain, a key attribute of a public blockchain, trustworthiness, is not a given because it can be controlled by a central authority.

A permissioned blockchain could give the best of both worlds. Participants in the blockchain could decide who can participate and which transactions are made public. The blockchain can still offer the advantages of integrity and security. Although people control the blockchain, the transactions are secure and cannot be modified in a veiled way (if implemented appropriately).

An independent IT company could take over the operation and maintenance of a permissioned blockchain, which would mean that the prosumers only have to take care of the connection to the network. A separate blockchain for each smart grid may be too complex in the current state of development, and the danger of security loopholes too high due to implementation errors.

Since an electric utility is no longer the focal point of the energy network, considerable resistance to a shift to decentralisation might occur due to existing players in the market. The following (translated) concern from the Federal Association of Energy and Water Management highlights this point: "The emancipating effect of the technology can shift the balance of power in the direction of customers and thus turn prosumers into direct competitors of established suppliers in cooperation, for example, with advisory start-ups" [40]. The fact that the state is a shareholder in many energy companies could present further barriers.

From this nonconclusive overview, it can be deduced that a decentralised electricity market has advantages. The risks come in the form of cyber-security and an un-adapted legal situation. The energy and infrastructure change costs must also be included in the risk assessment. The issue of energy consumption is likely to be mitigated due to further development, in particular regarding innovations in the area of consensus algorithms. Newer developments and second-layer solutions such as the lighting network can make implementation more economical.

Thus, prosumers, manufacturers, and public institutions may be interested in the extent to which the blockchain will be used for new installations of smart grids and which technologies will be employed. Whether the blockchain will realise its potential as a more reliable network with more efficient real-time trading of electricity will become apparent in the coming years.

5. Conclusions

While the blockchain principle is still most commonly associated with cryptocurrencies such as Bitcoin, its usability in different contexts and sectors has been pointed out both in theoretical work and through real-life experimentation. One of the more promising areas for the implementation of blockchain systems is the energy sector, where the blockchain may prove an effective response to some of the major present challenges, such as a drive towards decentralisation/democratisation, a necessity for more sustainable configurations, and a need for increased resilience. While blockchain energy offers many advantages due to its increased security, transparency, and flexibility, there are also numerous disadvantages and risks, both on the system level—mainly related to energy sector incumbents—and on the level of the technology itself. While the technology-related challenges are representative for the relative newness of the concept and many of them are solvable at least in principle, finding solutions for system-level challenges will strongly depend on current and future drivers and mega-trends in the energy regime, as well as pressures by the broader socio-econo-geographic landscape in which the regime is operating. Further, not all socio-technical configurations for blockchain energy systems are equally performant or suited for the same setting. For example, while a public blockchain energy market would represent a more desirable configuration in terms of transparency and inter-prosumer exchanges, such a market is hardly feasible in practice, whereas the private blockchain markets with potential centralised control mechanisms have already been realised even though they provide lower levels of trustworthiness and transparency. Overall, blockchain energy is a highly interesting concept for the future of regional, national, and international energy systems, but also one whose success strongly depends on major socio-technical trends and development trajectories in the energy sector. In order to influence these trajectories, both academic and practitioner supporters of blockchain energy need to combine further research and development with practical implementation and applications in a real-life setting, demonstrating the utility and performance of the concept in practice to relevant stakeholders and decision-makers. From a technical and IT point of view, this includes, in particular, the consideration of the "security by design" concept. Cybersecurity is a topic that should not be neglected, particularly in the field of blockchain energy.

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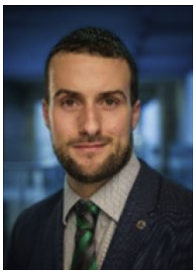

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