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Blockchain in the Energy Sector

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The digitization of the energy industry continues to pick up speed. A new driver of this rapid development is currently the blockchain technology, which could, according to many experts, usher in the next stage of development of the Internet. Blockchains have the potential to optimize energy management processes in almost all stages of the value chain while coping with the rising complexity of the increasingly decentralized energy system.

For the integration of a large number of prosumers into the energy system, the underlying IT architecture will have to ensure an efficient and secure distribution of data. In this respect, the blockchain technology has

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made headlines in tech, and finance press, being mostly known for a utilization as decentralized databases in financial deployments, most famously Bitcoin. After the technology made its first appearance in Nakamoto (2008), diverse authors have centered articles around blockchain-related issues. Among those, most focus on the technological architecture and its characteristics (e.g. Decker and Wattenhofer 2013; Pilkington 2016), anonymity and privacy (e.g. Zyskind et al. 2015), or the applications in finance (e.g. Fanning and Centers 2016). Today, the fundamental necessity of information systems (Wissner 2011; Colak et al. 2016) as well as accompanied potentials and value increasing applications (Gungor et al. 2013) have finally raised awareness in the energy sector (e.g. Albrecht et al. 2018). A study from the Federal Association of the German Energy and Water Industries (BDEW) analyzes the potential of energy-related applications and corresponding challenges (BDEW 2017).

Digitalization and decentralization are putting households and companies in the focus of the energy system, as they increasingly participate actively in market affairs through small-scale interactions. However, not only users and consumers may benefit from the blockchain technology. From an economic point of view, the possibility of increasing network utilization and efficiently organizing the allocation of flexibilities of any size seems particularly interesting. The ability of a blockchain to make even the smallest transactions cost-effective ultimately means new degrees of freedom, for example for the provision of control energy, direct electricity trading between market players or so-called "shared investments". In combination with the digitization of metering processes, blockchain technology supports new forms of product differentiation, including generation type, location, and time. Correspondingly, there are already a significant number of specific pilot projects in all value-added stages of the energy industry. Examples are the charging infrastructure for e-mobility, the certification of green and regional electricity, neighborhood and tenant electricity concepts, the provision of control energy and wholesale electricity. These are analyzed in course of the chapter.

The Transition of the Energy Sector and the Upcoming Market Challenges

The emergence of renewable, distributed energy resources (DERs) and smart grids is expected to create a network, in which billions of devices could automatically communicate with each other. The increasing share of these energy resources might establish a zero marginal cost market in which single units of generated power will have no significant costs anymore (Schlemmermeier and Drechsler 2015). Concurrently, competition impacts on wholesale prices and margin rates. Utilities are pressured to adjust to the change. The energy market is facing changes induced by technological and socioeconomic developments. The following trends can be observed (Edelmann 2014):

- The **energy generation** transitions from conventional thermal power plants to DERs, often renewables (Fig. 2.1). This induces fluctuating supply, increasing uncertainty, and a demand for information services;
- **Energy trade** becomes more complex. Local markets are being established, opportunities emerge, streamlining the digital infrastructure gains in relevance;

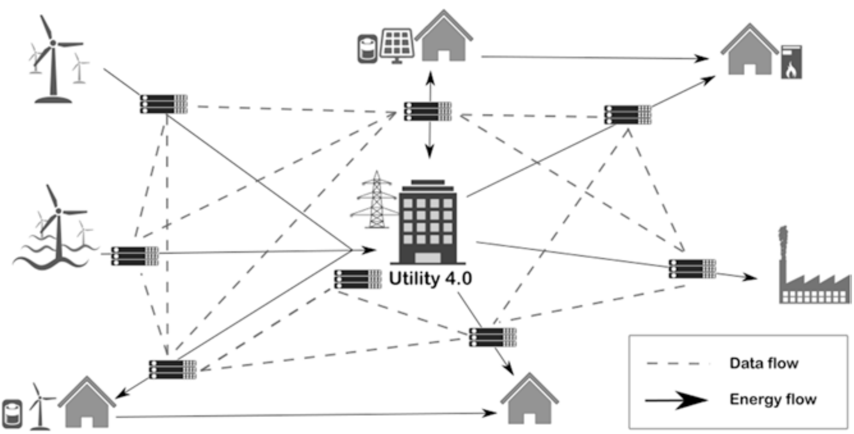

Fig. 2.1 Future energy market

- The **energy distribution**, now utilizing bidirectional flows of energy and data, is getting more dynamic (weather reliant plants, storage);
- The **metering infrastructure** is getting digitized. The smart meter rollout (in Germany beginning in 2017 [EnWG 2011]) is starting to replace analogous meters with smart meter gateway (SMGW) tethered devices;
- **Customer relations** are being confronted with a new kind of emancipated customer, who is less reliant on the utility and who takes social and environmental issues into consideration.

According to Dalkmann (2014), stated trends can be classified in three major socioeconomic phenomena: (1) *Volatility*: The heterogeneous generation is causing high fluctuations. Accordingly, supply and price are subject to high levels of uncertainty. (2) *Locality*: DER such as power-heat coupling plants, photovoltaic installations, and biogas plants are becoming more popular for residents and local organizers. An increasing share of energy demand can be provided locally, making the grid-balancing a challenging task. (3) *Participation*: The traditional role of a utility is to locally provide a commodity to passive customers. The changes of the energy market have an empowering potential for customers, enabling them to optimize domestic consumption and to switch retailers. The establishment of local community projects to increase the share of local and green power is one instance. In Germany, households, small businesses, and local governments invest in more than 800 of these projects (Ott and Wieg 2014). This may encourage utilities to actively pursue the development of more differentiated products to saturate these emerging segments of demand.

In Kolks et al. (2012), the authors identified competition as a major challenge for local utility companies. In the last few years, multiple German cities started to either remunicipalize formerly privatized utilities or establish new ones. Consequently, local and national competition increases while customers are able to choose the utility providing the most suiting retail products. The diversification of energy demand is another challenge for utilities. Customers may demand more options for the individualization of their consumption, controllable, and autarky-fostering solutions, representing an emancipated relationship to the company. Utilities ought to develop products that enable risk-seeking customers to optimize their individual costs while providing risk minimization for risk-adverse customers.

Along with the transitioning environment, the business needs of utilities change as well. Due to the decrease in volume and profitability of the conventional business areas, companies ought to discover or create new value streams to foster growth. This includes the reconceptualization of customer relation strategies. Utilities can generally be classified as risk-averse. Innovation on information and communications technology gets easily disregarded. Most do not operate an internal research and development (R&D) department, spending less than 1% of net sales on R&D (European Commission 2013; Daim et al. 2013). This innovational inertia creates opportunity for market-external agents, aiming to secure their share of novel business areas. According to Edelmann (2014), the following business areas qualify for market penetration by external agents (Table 2.1).

Accordingly, in the studies by Edelmann (2014) and Schlemmermeier and Drechsler (2015), the authors identify critical issues to be in the focus for changing energy business models. The "winners of the coming smart market" will have to satisfy a number of conditions. They need a clear vision for a strategic positioning in the market, as well as for a product portfolio and a targeted market share. They need to build up internal

Table 2.1 Exogenous sources of competition in transitioning energy markets (based on Edelmann 2014)

Area	Task	Competitors from…
Smart home services	Home Automation, Energy management	Entertainment industry, Automotive
Customer relations	Billing, visualization	Telco, Retail, Technology
Metering	SMGW-Administration, Remote meter reading	Technology
Data management	Data mining, Analytics, Load profile segmentation	Business analytics
Grid and distribution	Grid monitoring, Microgrid operations	Industry
Energy generation	DER, Renewables, Storage	Technology, Automotive

proficiency as well as business cooperations with intermediaries and service providers. Furthermore, innovation capabilities and technological excellence will play a crucial role, in combination with a strong corporate identity and customer focus. These developments and contemporary challenges of the energy sector display a necessity for technological innovation to transform utilities' business processes.

The generation of electricity is increasingly determined by decentralization, digitization, and decarbonization. As a result, it is becoming more and more fragmented, the number of prosumers, that is consumers who are also producers, is steadily increasing and DERs, such as PV rooftop installations, batteries, and electric vehicles, will continue their growth in the coming years. In addition to loads of all kinds in households and businesses, they are increasingly being controlled via the Internet. The shift in the value chain to a bidirectional relationship between energy production and consumers is gradually progressing. At the same time, the economic pressure is steadily increasing to make distributed resources usable for both the grid and the market. In the next chapter, we will outline how blockchain technology promises to reshape the interaction between different market actors.

The Promises of Blockchain in the Energy Sector

The blockchain technology promises to be able to organize and track very small energy flows and control signals at the lowest transaction costs. It fits seamlessly into strategies that put the customer at the center. Overall, processes and business models are increasingly determined by the changing needs of customers. As a result, direct investments in generating plants, the purchase of small quantities, as well as their processing, billing and flexible delivery make the overall energy system much more complex overall. Blockchain technology promises to contribute to managing this emerging complexity through controlled data usage (data sovereignty) and direct interaction between actors (disintermediation). Possible applications of blockchain technology in the energy sector are discussed intensively. In 2016, a study by the German energy agency (dena) analyzed some applications about their potential. Significant potential was identified, above all, in direct transactions between customers, including financial settlement, as well as in the areas of clearing and settlement and certifications of origin. A study by the BDEW, published in 2017, further analyzes specific use-cases as well as the main determining success factors. The reduced need for intermediation (disintermediation) can simplify many processes, such as the change of providers or even the organization of ancillary services, and possibly organize them more cheaply. Equally feasible is the automated transfer of duties, levies, charges, or compensation through a blockchain. Complex documentation processes can be eliminated or reduced for all actors involved. It should be noted here that the boundary between the optimization of existing processes and the redesign of processes is fluid.

In addition to distributed generation, the number of loads of all kinds rapidly increases that are controlled via the Internet (production machines, lighting, ventilation, vehicles, heaters, etc.). Irrespective of the question of suitable market design, the integration of these IoT resources into the electricity system as active market participants is urgently required from an economic perspective: unused capacities and (long term) storages represent opportunity costs. The direct interaction of devices promises to improve the utilization of networks and the allocation of flexibilities significantly. In such a real-time energy industry, millions of devices are fine-tuning their behavior based on market and network signals. For a realization, however, it is necessary to carry out each of these microtransactions safely and efficiently and to make them comprehensible. Blockchain technology promises here to be a major contributing factor. New degrees of freedom may also arise for the design of the balancing group management, if a real-time management is possible. If small-scale infeed and outfeed of electricity becomes cost-effective, then product differentiation by type, location, and time becomes possible (e.g. the detection of local green wind power). Due to increasing self-sufficiency, neighborhood electricity and the usage of electric cars, the typical 4000 kWh household will no longer be the standard in the future. A resulting increase in the number of prosumers and the ongoing electrification of the heating and transport sector are expected to generate considerable pressure for local supply and demand to be networked. This also applies to the aforementioned expansion of Internet-enabled consumption and generation facilities. The discussions about neighborhood and tenant electricity models are an indicator for the evolution of decentralized market scenarios. Ultimately, the speed of these developments will significantly affect the opportunities for blockchain technology.

Categorization of Blockchain Types

Public (Permissionless) Blockchains

The most popular blockchains, such as Ethereum or Bitcoin, are permissionless and public. In principle, they are accessible for everyone, given the appropriate infrastructure (Table 2.2). Participants are usually anonymous to other participants and represented only by a random ID as personal address. In first instance, there is no central provider to supervise the ongoing traffic. Public blockchains typically rely on the so-called Proof-of-Work (PoW) consensus mechanism for validating new data blocks. For this, miners compete against each other to solve a computa-

Table 2.2 Criteria for public, private, and consortium blockchains (based on BDEW 2017)

	Public	Private	Consortium
Access	Permissionless	Permissioned	Shared permissioned
Personal Information	Pseudonymity	Known	Known
Device Authentication	Not required	Required	Conditional
Consenus Mechanism	PoW, PoS	PoA, PBFT	PoW, PoS, PoA
Security	Decentralized control	Single point of failure	Various
Transaction Speed	Low (PoW)	High	Higher than public
Energy Consumption	High (PoW)	Low	Rather low
System Costs	High	Presumably low	Medium to low
Individual Costs	Low	Rather high	Various

tional puzzle, where the winner gets to update the database and typically receives a reward in the specific digital currency (Swan 2015). Then the process starts again from the beginning for each new block. The correctness of the solved puzzle and the integrity of the whole blockchain is verified by all participating servers. This advanced consensus mechanism makes trust between individual actors obsolete, as the majority of all participants supervises the entire history of transactions. The reliability of a public blockchain heavily depends on a sufficiently high number of participants as miners, who provide the needed computational power and storage capacities. In various initiatives, tremendous effort goes into working on alternatives to the PoW with less resource consumption, such as the Proof-of-Stake (PoS) (Buterin 2014). If these efforts are successful, public blockchains have two major advantages over private or consortial blockchains: Firstly, it allows the participation of random devices (machines, mobile phones, tablets, etc.) that are unknown to each other and not needed to be trustworthy. Secondly, there is no necessity that a consortium or private provider has to admit new blockchain-based applications. In a future IoT scenario, with random devices communicating on a near real-time basis, these two characteristics may prove fundamentally important.

Private (Permissioned) Blockchains

For permissioned and private blockchains, access is only granted to known participants, who might have rights to read and/or write data. The provider has full control over the blockchain and he knows all participants a priori. Thus, in most cases, private blockchains do lack the properties of anonymity and irreversibility. The provider generally has the possibility to set back certain processes in the blockchain, even though specific designs may vary. The abandonment of the PoW consensus mechanism and the irreversibility of the blockchain could greatly increase the processing speed and scalability. The validation of single blocks is thereby possible at much lower consumption of resources, as not all participants are simultaneously working on the solution of the algorithmic puzzle. An alternative to the PoW consensus mechanism for private blockchains is the Proof-of-

Authority (PoA), where only a single node generates new data blocks. With private blockchains, it is possible to develop and deploy new applications rapidly. The most promising fields of application may be internal business processes, targeted toward a high throughput of data. It is possible to cut off and archive the blockchain at frequent intervals, for example yearly, which can reduce the size of the storage volume significantly. Private blockchains do not necessarily need an underlying digital currency, as no financial incentives need to be set for miners.

Consortium Blockchains

Consortium blockchains (or special-purpose blockchains) as semiprivate blockchains (shared permissioned blockchains) are oftentimes regarded as a compromise between public and private blockchains. Here only verified participants are allowed to validate blocks. Optimized consensus algorithms permit significantly faster transactions than public blockchains. They do not necessarily need an underlying digital currency, although tokens can be useful for setting incentives. Generally, consortium blockchains offer the possibility to be tailored toward the specific requirements of the energy market, for example by giving up the property of anonymity or by an increase of the transaction volume depending on the application. Currently, the Web Energy Foundation plans to establish and operate a consortium blockchain, specifically designed for the energy sector (Rocky Mountain Institute 2017). In this respect, the question of interoperability between different types of blockchains (public, private, and consortium) and industries is regarded as one of the key success factors of the blockchain technology (Underwood 2016).

What Are the Most Promising Areas for Blockchain Applications in the Energy Sector?

At present, a large number of energy providers and startups are working on the testing of blockchain solutions such as Ethereum, Hyperledger, BigChain, or Tendermint. In the foreground is usually the optimization of energy management processes such as billing, management of data, or processes for the change of electricity suppliers. The classic value chain of the energy industry is becoming increasingly interconnected and new applications can no longer be assigned exclusively to one area. In the following, some selected application fields are shown and the impact on the classical value chain is outlined.

Charging Infrastructure for E-mobility

The use of electromobility requires an area-wide charging station infrastructure. A very decentralized distribution and a large number of different operators make today's billing procedures very complicated. For example, the process of recognizing the user upon authorization at a charging station may currently be delayed due to a multitude of requests at different instances. Through the use of a blockchain method for detecting the vehicles and for communication as well as billing of the amount of electricity purchased, the processing speed can be significantly increased. The consumer at a public reference point could be immediately recognized and settled. This leads to a comfort gain for the customer, cost reduction for the provider, as well as detailed billing of the actual electricity purchased. In addition, the customer remains in control of his mobility data at all times. A current project for this is, for example, Share & Charge of Innogy and slock.it, in which the billing of the electricity purchased for electric cars is tracked and billed based on blockchains. Participants will also be able to make their private charging stations available to other electric motorists. Payment and billing is done automatically via blockchain-based smart contracts.

Certification of Energy Products

Customers comparing electricity tariffs containing exclusively renewable energy sources are oftentimes lacking the required information about the origin of their accounted electricity. Even though over 700 different retailers in Germany offer green electricity tariffs, the standards between individual contracts vary significantly. In many cases, only a certain percentage of the electricity comes from renewable sources. In order to provide green electricity, individual renewable power plants are typically certified by a number of institutions in a costly process. The energy generated in these plants can then be traded as renewable energy certificates (Brey 2013). The implementation of a blockchain-based system could significantly increase the transparency by making transactions between producing unit and consumer publicly available and thereby raise trustworthiness of green products for end consumers.

The tamper-proof decentralized storage of data in a blockchain enables a transparent documentation of transactions that can be reviewed by all users and is therefore comprehensible. Certificates for renewable and regional electricity production, for example, can be documented on blockchain from the beginning of the production stage. As a result, products such as green and regional electricity can be developed, which are undoubtedly traceable to a source and invulnerable to manipulation. In addition, certificates for tradable emission or CO_2 products are conceivable.

Generating plants, such as PV rooftops or CHPs, can write their own generation services directly into a blockchain via a terminal connected to the Internet. The documentation of the feed-in or any consumption is, therefore, guaranteed. However, it has to be ensured that the system on site (generation plant, measuring equipment) is correctly authenticated and that therefore no incorrect values are invariably written to a blockchain. For example, it must still be ensured that it is an actual PV system that feeds-in locally and that the generated electricity is billed via a calibrated meter.

One solution already available on the market is the so-called GrünStromJetons of startup StromDAO. These assess the current electricity consumption of a household with the green electricity share present in the respective postal code area at the time of consumption in the regional electricity mix, the so-called green electricity index (based on regional generation structure, network topography, weather forecast, and load profile). The participating households receive units of the tradable cryptocurrency GrünStromJetons, depending on their green electricity purchase, with more GrünStromJetons for more related green power. Thus, the tokens provide information on the sustainability of individual electricity purchases or indirectly on the network efficiency of consumption behavior. Furthermore, in addition to the criteria of time and place of power consumption or power generation, it can also be differentiated according to the contribution to grid stability as a criterion of the value for the grid. This, in turn, can serve as a basis for corresponding electricity tariffs for private customers. For the heating and gas market, the examples given are basically transferable.

Neighborhood Models and Microgrids

The ability to conduct secure transactions between agents without an intermediary, to account for them accurately, and to establish automated contractual relationships through smart contracts, enables not only new energy products but also new options for tenant electricity and neighborhood models. The Brooklyn Microgrid in New York City has experienced great media attention in 2016. The blockchain startup LO3 Energy is realizing a peer-to-peer exchange platform (i.e. exchange directly between private subscribers without intervening intermediaries) for electricity (e.g. Mengelkamp et al. 2018). Apart from the regulatory environment, this project fulfills all relevant components of an efficient microgrid energy market, for example microgrid, grid connection, information system, market mechanism, price mechanism, and energy management system. The focus of interest is the market for peer-to-peer solutions, especially for companies: It is expected that especially microgrids and distribution grids are increasingly turning into so-called "transactive grids", in which network-specific requirements and restrictions will be taken into account. By linking with blockchain technology, this creates the prerequisites for transparent and efficient energy trading between a large number of participating systems and the most diverse players, especially in systems with many decentralized units. As a result, the efficiency of the overall system might be increased and customers might profit from cost advantages and opportunities for new business models.

The common basis of the various tenant electricity and neighborhood models is that the generated energy quantities are recorded and written into the blockchain via intelligent measuring systems. There, the transactions are automatically executed and documented between the participants. Decentralized and self-managing, smart contracts ensure that electricity is demanded, for example, when a price threshold is undercut or green electricity or local electricity is available. Billing is also automated. One way to establish an appropriate business model is, for example, the operation of a local donor network, which supports providers to generate regionally renewable energy. For this reason, Conjoule's pilot project brings together private photovoltaic systems with local buyers based on the blockchain. In addition, there is the opportunity to automate energy management for households via smart contracts. Flexible consumers are shifting their demand over time or storing cheap, local, or green electricity. Under certain circumstances, active participation in other markets, such as the market for regulatory power, may be possible.

Local Smart Markets and Energy Trading

Fluctuating renewable energy generation forces utilities to cover their energy demand in smaller time horizons as the actual amount of produced energy in the future is subject to uncertainty. The rising number of decentralized prosumers demand an active participation in the energy market. A central energy trading platform, such as the European Energy Exchange, is not entirely suitable to address local energy imbalances in a decentralized energy sector. Local platforms, on the other hand, induce three major problems. First, operating a platform is costly, as each transaction has to cover its individual costs. Second, a platforms provision would be organized by a single business, performing as an intermediary and charging service fees. Third, the IT infrastructure of a platform usually remains on a single server system, limiting its resilience against attacks. The blockchain technology can potentially solve all three problems. First, blockchains are decentralized and implemented in all participating smart meter devices. A trustful intermediary is not required since the technology allows trustless interactions. Second, a blockchain network is based on an almost autonomous code; therefore, transactions can be processed by smart contracts. Thus, the absence of third parties may potentially decrease transaction costs. Third, based on the decentralized and cryptographic characteristics, blockchains can provide a high resilience against attacks.

Overall, blockchains offer great potential in electricity trading and are a key enabler of balancing and managing the grid from the bottom up instead of today's top-down approach (Morris 2017). Blockchain technology promises direct and anonymous trading in a variety of power market products without the need to resort to a marketplace or intermediary. The main reason for this is the fact that the blockchain allows trusted transactions between unknown actors. An implementation of this idea was presented, for example, with the blockchain application Enerchain in November 2016 and is being carried out by 22 companies in a pilot project. An expansion to balancing group management is also conceivable in the future. Thus, the transmission of relevant information can be made more efficient as well as the load and generation forecast by integrating a variety of micro devices. The actual consumption and production values can be automatically recorded, compared with the forecast and calculated. While technically the balancing group size can be reduced down to final consumers or terminals, among other things the balancing group responsibility raises a number of unanswered questions (e.g. organization of residual electricity supply).

Asset Management

The installed measuring technology and the transfer of data into the blockchain can also be used for asset management. The monitoring and documentation of plant conditions enables efficient management of these plants. This provides operators, regulators, investors, and insurers with accurate and reliable information on the nature and condition of the asset and its ownership status. From this predictive maintenance cases can be constructed, that is, measures for the anticipatory maintenance of plants. Other applications include proving the operational capability of, for example, wind turbines in the event of network bottleneck-induced feed-in reduction, the tamper-proof and distributed storage of ownership and its transaction, as well as efficient auditing. Cost reductions can be achieved here through disintermediation, that is, the elimination of an intermediary, and process acceleration as well as increased resilience of plant monitoring and control that is related to decentralization.

The overlaps between the applications shown here underpin the previous statement regarding the breakup of the traditional value chain by new technologies. Just as the individual economic sectors of mobility, energy and communication are becoming increasingly interconnected, the use of innovative technologies, such as blockchain, blurs the boundaries between the parts of traditional energy supply companies. This creates the need to redesign and rethink conventional corporate structures.

Key Determinants for Blockchain in the Energy Sector

Technical Limitations and Determinants

The applicability of the blockchain technology for processes in the energy value chain depends on technical criteria, such as transaction speed, energy consumption, IT security, and reliability, but also on economic factors and the general acceptance of the technology.

Technical Challenges

Comparable to other fields, the success of blockchains in the energy sector depends largely on the overall development of this technology. For instance, the resilience against internal or external threats has yet to be investigated. That incorporating smart contracts on the blockchain causes inherent vulnerabilities toward outside attacks shows the prominent case of the Ethereum-based application of the Decentralized Autonomous Organization. After attackers were able to temporarily drain a large amount of Ether by exploiting a certain loophole in the code of the blockchain, the organization was eventually able to retrieve the stolen Ether by rolling back the transactions (Del Castillo 2016). However, concerns remained that this so-called "hard fork" might undermine the perception that the blockchain is immutable, and that contract agreements, once settled, would be final. Even though this particular case can be traced back to flawed design, it also raises questions about how decentralized the blockchain really is if major threats should occur.

The cost-effectiveness of blockchains compared to other technologies and the current intermediary-based system will be a major determinant. A network based on P2P-transactions is only feasible if it is able to lower transaction costs significantly. The current versions of blockchains, however, do not come at zero cost, since the so-called PoW concept for the generation of blocks requires extensive amounts of computing capacity (Tapscott and Tapscott 2016). Upcoming blockchains might incorporate a different validation concept, the PoS, which promises further improvements in efficiency (Watanabe et al. 2016). A functioning PoS mechanism could significantly reduce the needed computational capacity, as it is not needed that all connected processors compete against each other on a solution to an algorithmic puzzle, as it is in the PoW. However, this might in return exhibit certain risks regarding the consensus mechanism and allow single participants unwanted exploitation possibilities. More alternatives are being tested out, for example the Delegated PoS by Steemit, EOS, and BitShares or the Byzantine Fault Tolerance by Ripple (Glazer 2018). One of the biggest technical challenges is the scalability of transactions inside the blockchain network. Current blockchains are not yet suitable for high-frequency transactions, especially when taking transaction fees, for example, as the 0.0001 Bitcoin per transaction for the Bitcoin network. In addition to that, the shared ledger will grow much faster. Due to the fact that each participant needs the full ledger to be part of the network, the integration of new participants will be more difficult. The privacy properties of blockchains might constitute a problem as well. The technology provides pseudonymity with a unique address, but it is possible to identify entities behind the blockchain address by analyzing the data on the blockchain (Shrier et al. 2016). Another critical issue is the standardization. The blockchain is a young technology and each initiative is developed on its own individual solution. Standardized blockchain protocols allow the development of software that is more geared to market solutions.

The consumption of permissionless blockchains stems from the computational effort to execute the PoW consensus mechanism. There are no precise calculations for blockchain's energy consumption because the load of the participating devices is not available. However, approximations suggest the total power consumption for instance for the Bitcoin blockchain to be comparable to a developing economy (Digiconomist 2017). The PoS mechanism exhibits lower power consumption since less participants are required to verify transactions. Permissioned and consortium blockchains perform verifications on only a few nodes or cloud solutions and do not consume more energy than conventional database systems. The ecological factors of energy consumption reveal an underlying conflict between decentralized technologies and the aim for green energy. While western enterprises are using permissionless blockchains to reduce transactions costs, datacenters in developing countries fueled by coal may become new pollution havens by verifying their transactions.

Transaction Speed

Already today, the procurable capacity of public blockchains in transactions per second (TpS) is sufficient for applications such as the certification of green electricity and local community/neighborhood power supply. For a wide-spread use of the blockchain technology, however, the limited transaction speed of public blockchains is one of the key limiting factors, e.g., Ethereum currently allows only 10–20 TpS. For comparison, the Visa Network has a maximum capacity of 56,000 TpS and makes 2000 TpS on average, and PayPal runs an average of 155 TpS (Mougayar 2016). A future energy market, with a great number of devices communicating in real-time, sets high requirements for the number of transactions. Current blockchains are not yet suitable for high-frequency transactions (Fig. 2.2).

The reason for this low speed is the employment of the PoW consensus mechanism that is used to validate the transactions. In the medium term (Serenity Release, expected in 2018), the public blockchain Ethereum intends to switch to the less computation-intensive and thus faster PoS consensus mechanism. The promise associated with this change is an up to ten-fold acceleration of the transaction speed. Furthermore, the idea is to further increase the speed by splitting up and parallel processing the transactions in the so-called sharding consensus mechanism. In addition, the shared ledger will grow fast. Since each participant in a public blockchain network needs the full ledger to be part of the network, the integra-

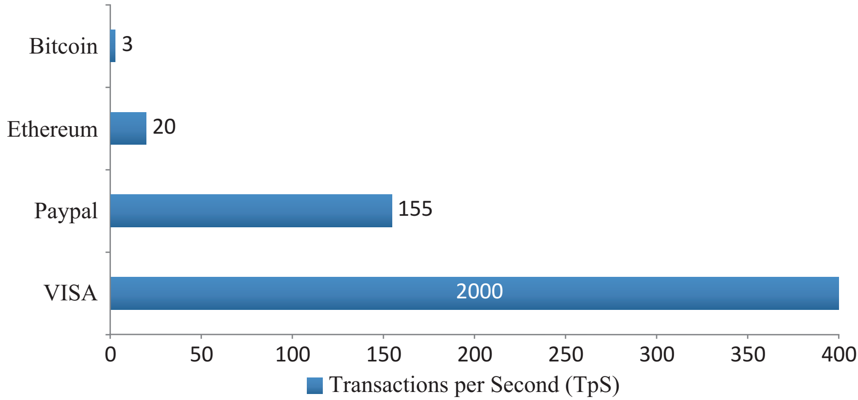

Fig. 2.2 Transaction speed of payment systems (Based on Mougayar 2016; BDEW 2017)

tion of new ones will be difficult. Today, the Bitcoin blockchain, for example, has a size of about 80 gigabytes (Blockchain Info 2016). The future energy market, with a vast amount of production and consumption units communicating on a near real-time basis, sets quite high requirements regarding the number of transactions.

Private blockchains generally do not exhibit technology-related restrictions regarding their transaction speed. As all nodes within a private network are known and regarded trustworthy, they can handle the validation of transactions in an uncomplicated way. This can be done through the so-called PoA mechanism, which might be better suited for high transaction speeds.

Operation and Transaction Costs

The cost-effectiveness of blockchains compared to other technologies and the current intermediary-based system will be a major determinant. A network based on P2P-transactions is only feasible if it is able to lower transaction costs significantly. While the cost of operating private blockchains is generally relatively low and comparable to cloud solutions, in actual practice, the costs mainly depend on the chosen design and thus cannot be estimated without better understanding the specific application requirements first.

On the other side, the costs are perceived as a key obstacle to the spread of the public blockchain technology. Operating the Ethereum network currently costs about 93,440,000$ per year and the Bitcoin network approximately 657,000,000$ per year (Slock.it 2017). The operational costs of an application on the public blockchain mostly consist of the total of transaction fees required to operate it. A simple Ethereum transaction costs about 21,000 gas, which translates to about 0.12 cents at an exchange rate of exchange rate of 300 $/ETH (Wood 2014; Etherscan.io 2017). Compared to existing payment service providers (e.g. a transaction with PayPal costs € 0.35 plus 1.9% of the transaction volume), blockchain transactions are already inexpensive. Average-sized transactions are, therefore, already economically feasible through public blockchains. However, these are still too high in the context of microtransactions. For instance, a typical new refrigerator consumes energy of about 12 eurocents per day on average (150kWh/a × 29 cent/kWh). Flexible purchases of small amounts of electricity from different sources with several transactions per day can thus not be realized economically.

Upcoming blockchains might incorporate a different validation concept, the PoS, which promises improved efficiency. A functioning PoS mechanism could significantly reduce the necessary computational capacity, since not all connected processors compete against each other on an algorithmic puzzle, as in the PoW. This, however, might pose certain risks regarding the consensus mechanism, possibly allowing participants unwanted exploitations. One of the biggest technical challenges is the scalability of transactions inside the blockchain network. If companies manage to reach a critical mass fast enough then private blockchains could prevail. A possible reason for this development is that private blockchains lure more capital, as they promise to develop a proprietary application. In general, the development of two approaches is also conceivable: a peculiar altruistic public blockchain part and a consortium or private blockchain part for business applications. Due to the competition between the various systems, the costs will possibly continue to fall. Furthermore, as high license and software costs are no longer required, consumers are faced to lower costs due to the fact that these services are handled via the blockchain, for example for the neighborly trade of electricity and the exchange of flexibility.

Costs

While the cost of running private blockchains is relatively low and comparable to cloud solutions, the costs for public blockchains are perceived as a major obstacle to the spread of the technology. A simple Ethereum transaction without smart contracts option costs about 21,000 gas (about 1.5–3 cents). By combining transactions, this value can be roughly halved. Compared to existing payment service providers (for example, a transaction at PayPal costs around € 0.35 plus 1.9% of the transaction volume), blockchain transactions are already cheap. As a result, transactions can now be economically represented using public blockchains. In the context of microtransactions, however, these are still too high. On average, a new refrigerator consumes electricity worth about 12 cents per day (150 kWh/a × 29 cents/kWh). Small-scale, flexible purchases of electricity from different sources (for example, from a neighbor with a PV system or a battery) and with multiple transactions per day cannot currently be economically implemented (using public blockchains).

Security

According to current knowledge, the PoW procedure is safe. So far, there was no hack of the actual blockchain, but only the applications on it. However, the security tests are still pending for the "proof-of-stake" mechanism. Private and consortial blockchains are classified as security-friendly between public blockchains and the use of non-blockchain-based methods. However, a common security vulnerability seems to be that very few developers develop these algorithms, and very few, in turn, review these algorithms, even though everything is open source. However, in order to guarantee resilience and thus a lasting security of supply in the energy industry, the entire system, that is the blockchain application as well as other parts of the system, such as smart meters and gateways, must withstand the safety tests.

What Is the Legal Framework for Blockchain?

General Contract and Data Protection Laws

The use of blockchain applications raises a variety of legal issues. These are increasingly being discussed and analyzed in the literature. The legal questions can be clustered into various topics, which can roughly be assigned to general contract law, data protection and IT security law, as well as energy law. A practically relevant case for blockchain applications are the so-called smart contracts. However, the term encompasses more than just contracts in the narrower sense of civil law. It goes beyond this by including the use of software that controls and/or documents or even triggers a legally relevant activity, for example, in the context of existing contractual relationships (Schrey and Thalhofer 2017). Thus, smart contracts can themselves be contracts or just a functional annex to a contract (Jacobs and Lange-Haustein 2017). Smart contracts are code-based and are handled by software applications. On the basis of specified conditions, the software automatically checks whether the predefined conditions exist and carries out the legally relevant activity (matchmaking).

There will be areas where smart contracts are unlikely to ever replace a comprehensive contract. At least more complex contracts are characterized by a certain degree of openness, which can be interpreted case-specifically by experienced lawyers. There are fundamentally different contractual principles that set limits for business via smart contracts. These limits ultimately define what properties should have trades that can reasonably be handled through smart contracts. As far as the conclusion of the contract itself by blockchain is concerned, it should be noted that the general civil law knows no immutable transaction history. These include, for example, the invalidity of contracts, the countervailability of contracts, the repayment after retirement, or the pending invalidity of contracts with minors until they are approved by the legal representative. Here, if necessary, a "reverse transaction" takes place (Schrey and Thalhofer 2017). For the related valuation issues in the analog world, the use of lawyers is required and in case of dispute even often the courts. As a result, transactions through smart contracts should be designed to be as little as possible vulnerable to such disruptions (Jacobs and Lange-Haustein 2017). The smart contract should have the ability to handle bad services at the program level (Kaulartz and Heckmann 2016).

Another relevant topic that sets limits for blockchain applications is data protection law. It accesses where personal data is processed and stored in the blockchain. These include, for example, the right of deletion stipulated from May 2018 by the EU General Data Protection Regulation as well as the "right to be forgotten" and the right to data portability (so-called "victim rights"). In a blockchain, neither data of single individuals can be removed nor finally transferred. Under certain circumstances, a regular complete separation of historical records is possible. Further consideration is needed here as to how the data protection requirements with regard to personal data in the blockchain can be implemented.

Last but not least, IT security regulations must be obliged. When exchanging personal data, network status data and master data originating from intelligent measuring systems, the high technical and cryptographic requirements of the Smart Meter Guidelines of the German Federal Office for Information Security (BSI) apply. In the case of business processes and in market communications, the corresponding requirements are formulated by the Federal Network Agency. Finally, operators of critical infrastructures are obliged to implement IT security standards, which are controlled by the Federal Office for Information Security in terms of their relevance with regard to security of supply.

Energy Regulation

The blockchain technology enables, among other things, the direct settlement of small amounts of electricity (and heat) between households and companies at low transaction costs. In this area, however, there are various legal requirements to consider. In this aspect, we focus on the German energy regulation here, but similar requirements can be found in most markets.

The requirements of the German Energy Industry Act (EnWG), the Electricity Network Access Ordinance (StromNZV), and the associated specifications of the Federal Network Agency are decisive for market access and the exchange of energy via a public network. The StromNZV regulates the conditions for feed-ins of electrical energy into supply points of the electricity networks and the associated simultaneous output of electrical energy at spatially remote consumption points of the electricity supply networks. For the use of the networks and the exchange of energy, it is necessary to conclude a network usage contract and a balancing group contract and to comply with the rights and obligations specified therein. The balancing group contract must be concluded between the transmission system operators and the balancing group managers and regulates the rights, obligations, the necessary information, and data exchange liabilities. These obligations apply to the exchange of energy between market actors, irrespective of which instrument (bilateral business, brokerage, stock exchange transaction, or blockchain technology) has been agreed.

Access to the balancing energy market is regulated by the StromNZV regulations, so that the use of blockchain technology is a new control and billing tool. It requires the prequalification of the plants for the control energy market and the participation in the tenders of the transmission system operators. In addition, the physical feed-in and billing is represented by the schedule management of the balancing group's electricity, so that the conclusion of a balancing group contract is also necessary for the exclusive provision of control energy to the transmission system operator. In addition, the rules of StromNZV for the provision of balancing power by final consumers must be complied with, so that in future small-scale plants and consumers can participate in the balancing energy market. To this end, the Federal Network Agency is aiming for a fix, the cornerstones of which were consulted in the spring of 2017. Thus, the provision of control energy can only be offered with strict control over a blockchain until further notice. Adherence to compliance for wholesale market operations also applies to quantities of energy traded through blockchain technology. For example, the obligation to report transaction data on wholesale energy transactions at European level is covered by the REMIT Regulation.

According to the EnWG, the obligation to report this activity to the regulatory authority is connected to an energy supply to household customers (§ 5 EnWG 2005). In order for the BNetzA to be able to perform its legally assigned supervisory tasks, it is necessary to have a deliverable address for administrative acts in the event of a regulatory application of blockchain. In the current report on digital transformation, the BNetzA is cautiously positioning itself on the subject of blockchain. The developments in terms of energy demand and computing power are to be awaited and tested against the background of security of supply to be guaranteed.

Energy supply contracts also have to meet specific legal requirements. Only by way of example, the obligation to include provisions on the duration of the contract, the price adjustment, termination dates, and notice periods, the customer's right of withdrawal, liability, and compensation arrangements for non-compliance with contractual services and information on the rights of household customers with regard to dispute resolution (§ 41 EnWG 2005). These requirements would at least have to be represented by a framework agreement on the basis of which individual electricity deliveries will be handled via smart contracts.

Conclusion and Outlook

The distributed system architecture of the blockchain harmonizes excellently with an increasingly decentralized energy industry. Greater IT security, efficiencies, potential cost reductions, and transparency are all powerful arguments in favor of blockchain technology that energy companies should use for themselves. New blockchain-based business models and applications are emerging at a fast pace. The maturity of blockchain technology in terms of speed, energy consumption, IT security, reliability, governance, interoperability, and cost-effectiveness is also rapidly evolving. However, it should be noted that currently almost all blockchain applications and projects are still far from having a high market penetration.

In the everyday life of the energy industry, the blockchain technology will only be competitive if important regulatory framework conditions have been clarified. In addition to fundamental challenges in terms of data protection or liability law, specific energy management issues remain unresolved at the moment. Blockchain applications make it possible to automate existing and new energy management processes and to present them in an immutable and transparent manner. Especially for the integration and orchestration of decentralized devices, systems and storages, the blockchain can serve as an instrument to enable real-time communication (e.g. storage recharge), documenting it with proof and providing it as a basis for further applications. A key success criterion will be the integration of blockchain applications into existing standard energy management processes and software. Once interoperability improves, penetration is expected to increase rapidly.

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