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# Blockchain technology applications in power distribution systems

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ABSTRACT

Blockchain technologies have attracted the attention of multiple control, operation, and planning entities in the energy industry. Blockchain technologies, which allow a shared and distributed database, allow for secure, transparent, economic, and automated operations in power distribution systems. In this paper, we introduce how blockchains work and can be utilized to enhance the operation of power distribution systems. We discuss multiple scenarios in which blockchain technologies have been implemented in power distribution systems. Also, we discuss pertinent challenges for applying blockchain technologies to power distribution systems and provide some measures to manage these challenges.

## 1. Introduction

Recent developments in power system technologies (e.g., distributed energy resources (DERs) and bidirectional communications) are leading to a restructuring and modernization of the existing power distribution system (Shahidehpour and Fotuhi-Friuzabad, 2016). Modern power distribution systems are expected to intelligently integrate these technologies and provide affordable, reliable and clean energy. The availability of communication infrastructure for information exchange will help distribution system operators implement automatic real-time monitoring and control, reduce operating costs, accommodate increased penetration of DERs, and better manage outages and emergencies (Shahidehpour and Fotuhi-Friuzabad, 2016). Overall, modern power distribution systems offer highly improved efficiency, reliability, and sustainability over the existing power distribution systems (Cleverism, 2020). However, modern power distribution systems still face significant challenges. For instance, bidirectional communication systems are prone to malicious attacks and leave the distribution power grid exposed to a wide range of security and privacy threats.

Blockchain technology is considered a promising solution to address the challenges in modern power distribution system. The introduction of blockchains provides a trustworthy environment for participants to directly interact with each other and carry out communications in a secure manner. Blockchains also provide faster and more transparent system operations. As a result, blockchains are considered a valuable technology to improve the security and efficiency in power distribution systems. For instance, the application of blockchain technologies in power distribution systems could enable automatic rerouting of power whenever outages or equipment failures occur, thereby reducing the number of outages and minimizing the adverse effects on the power grid.

This paper introduces the different applications of blockchain technologies to the power distribution system. We discuss the current major applications of blockchains in power distribution systems and further propose the challenges of applying blockchain in practice. The remainder of the paper is structured as follows. In Section 2, blockchain technologies are introduced. In Section 3, we examine and summarize several applications of blockchains in power distribution systems. In Section 4, we examine the major challenges associated with the adoption of blockchain technologies and how these can be managed. Section 5 reviews an example case study of a blockchain-based peer-to-peer energy trading platform in networked microgrids. Finally, the paper is concluded in Section 6.

## 2. Introduction to blockchain

Blockchain was first utilized in the cryptocurrency Bitcoin in 2008 (Nakamoto, 2008) and has since been rapidly developed to include multiple applications including financial services, real estate, health care, and business (Tama et al., 2017). Blockchain is a type of shared and distributed ledger or database that records information (e.g., transactions). The blockchain is available for public inspection by all network participants, and each participant has its own copy of the

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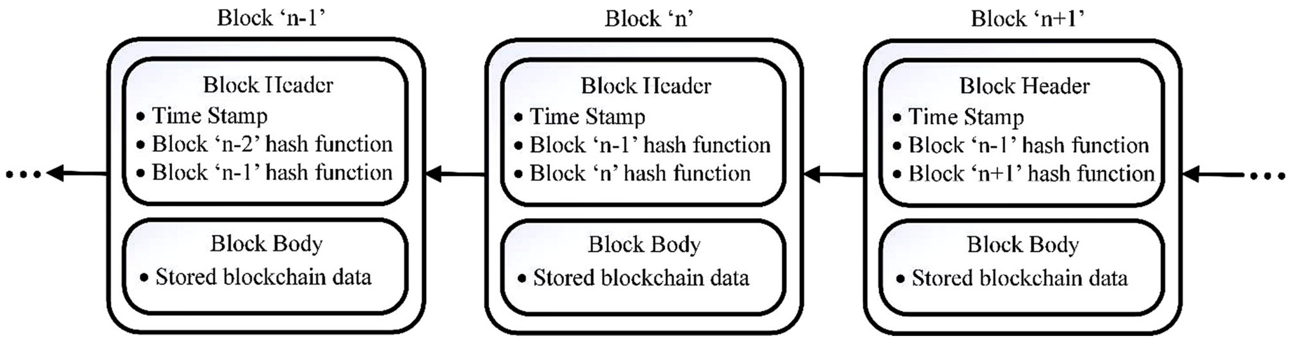

**Fig. 1.** General structure of a blockchain.

blockchain. In this section, we look further into blockchain technologies and their functions.

As illustrated in Fig. 1, a blockchain is a stack of blocks stacked in a way that each data block is sequentially connected to the previous block. Each block in a blockchain has a header and a body. When a block is established, the data is stored in the block body, while the current time stamp, and hash functions of the current and previous blocks are then stored in the block header. These hash functions are strings of numbers and letters and can serve as a unique address for each block. Once the data in block body is revised by malicious attacks, the corresponding hash function will change accordingly. As a result, the hash function of the edited data block will no longer match the hash function which has already been stored in the next block. Therefore, any attempt to change the data in any data block will be immediately flagged. Blockchains are thus secure and resistive to malicious attacks.

In contrast to a conventional centralized database, blockchains do not require any central authority to store and process data. If the network participants want to store the data in the blockchain, they will formulate the data as a data block and then propagate the data block to the other network participants. This propagated data block cannot be added to the blockchain unless all network participants agree on the validity of the propagated data block. After the new block has been successfully added to the blockchain, the updated blockchain will be propagated to all participants. However, if the data block is invalid, the data block is discarded and not added to the blockchain. The validation mechanism that participants use to validate the legitimacy of a data block is known as *consensus mechanisms*. With the introduction of consensus mechanisms, participants can quickly reach a mutual agreement on the validity of the data block. We will further discuss consensus mechanisms in detail in the following sections.

### 2.1. Classification of blockchains

Blockchains can be classified into three major categories, each with different characteristics and benefits. The architecture of a blockchain is heavily dependent on the access rights provided to the network participants (Andoni et al., 2019). The three different types of blockchains are further discussed in the following sections.

### 2.2. Public blockchains

Public blockchains are open-source databases available to all network participants. To be more specific, all participants can read the data stored in the public blockchain and participate in the consensus process for validating new data blocks. Public blockchains are fully decentralized and transparent since no participants can control or edit the recorded data. In addition, the participants in public blockchains are anonymous, which protects the participant's privacy. One popular application of public blockchains is cryptocurrency (e.g., Bitcoin). Each participant holds a copy of the blockchain and shoulders the responsibility of validating the data stored in blockchain. A consensus is reached when all network participants have validated the data. The above processes are achieved by employing consensus algorithms, which are introduced as follows:

#### 2.2.1. Proof-of-Work (PoW)

PoW is the first public blockchain consensus mechanism developed and was originally used by Bitcoin (Mollah et al., 2020). The PoW process is also known as *mining*. The network participants, named as *miners*, compete with each other to check the validity of new data block and further add new blocks to the blockchain by solving complex mathematical puzzles. Only the first participant solving the puzzle becomes the validator and will further add the data block to blockchain. To incentivize all participants to validate the data block, the participant who is chosen as the validator will be rewarded (e.g., rewarded with cryptocurrency). The scalability of PoW makes it very suitable for a variety of applications. Therefore, PoW is one of the most popular consensus mechanisms. However, PoW becomes quite vulnerable if one participant holds at least 51 % of the computational power around the blockchain network (Mollah et al., 2020). This is because the one participant who holds at least 51 % of the computational power can solve the complex puzzle more quickly than others and thus monopolize the rights for validating new data blocks. Since PoW requires participants to solve the complex puzzles, it takes significant time for participants to solve the puzzles and achieve a consensus. In addition, solving such complex puzzles requires large quantities of computing power and PoW is thus very energy-intensive.

#### 2.2.2. Proof-of-Stake (PoS)

PoS was proposed to overcome the drawbacks of PoW, particularly the problem with high energy consumption. Similarly, only one participant is chosen as the validator to add the new data block to the blockchain. In PoS, a random process is used to determine the participant who wins the privilege of becoming the validator. More specifically, the participants are required to pre-store a certain amount of cryptocurrency, which is frozen for a time period. The participants who stake their cryptocurrencies are the candidate validators and a random process is utilized to select the validator from these candidate validators. Finally, the chosen validator will add the data block to the blockchain. Generally, the participant with the biggest stake has the highest chance of becoming the validator. Similar to PoW, the validator will also be rewarded with cryptocurrency. Since participants are not required to solve the complex puzzles in PoS, PoS is thus faster, cheaper and less energy-intensive than PoW. However, in PoS, the rich stakeholders are more likely to be selected as validators. Therefore, it is unfair for the less wealthy network participants.

### 2.3. Private blockchains

In contrast to public blockchains, private blockchains are usually held and governed by a managing entity and only provide access to certified and trusted participants. Private blockchains allow participants to manage their data without revealing them to the public. Therefore, private blockchains have a *permissioned* characteristic which allows trusted participants to validate and record data at much higher speeds and with lower resource consumption. Proof-of-Authority (PoA) is the most frequently used consensus mechanism in private blockchains. In PoA, the entity managing the private blockchain will select several trusted participants as validators. The new blocks are verified and then added to the blockchain by the chosen validators. PoA is highly scalable as it only relies on a limited number of system validators. However, since the validators are determined by a managing entity, PoA mechanisms are less decentralized than mechanisms such as PoW. If a chosen validator fails to accurately verify the data block, the blockchain managing entity can penalize validators for failing to carry out their duties. An example of such penalties could be the network participant temporarily or permanently losing their validator status. Similar to PoS, PoA mechanisms require much less computing power than PoW (Alladi et al., 2019). PoA are most beneficial in industries where security and integrity are extremely important (e.g., supply chain management).

### *2.4. Consortium blockchains*

Consortium blockchains are known as an integration of private and public blockchains (Andoni et al., 2019). Similar to private blockchains, consortium blockchains only allow authorized entities to write data and participate in the consensus program. The data stored in consortium blockchains can be categorized as private data and public data. Private data can only be accessed by the managing entities, while public data can be accessed by all authorized network participants. Participants can control what data should be kept private or public. Consortium blockchains are generally used in the business industry to record cross-organizational business transactions (Xie et al., 2019). Due to the reduced number of participants in the network, the speed of transactions in consortium blockchains is very high. The comparison between the different types of blockchains discussed above is described in Table 1.

### *2.5. Smart contract*

Smart contracts are program scripts containing a set of rules and are stored in blockchains. Smart contracts are self-executable on the blockchain. If the set of rules and conditions of the smart contract have been met, the smart contract will begin to execute itself to completion. Once the smart contract is executed, it cannot be stopped or separated from the blockchain. Therefore, the smart contract cannot be tampered with. Smart contracts are stored on the blockchain with a unique address (Christidis and Devetsikiotis, 2016), which network participants can use to retrieve the contract. To further understand the operation of a smart contract, the following example is provided. Consider a situation where John wants to auction off a tablet to other blockchain network participants. John defines and deploys a smart contract on the blockchain network with the following conditions: (a) John is selling a tablet, (b) the highest bid wins, (c) the starting price of the tablet is set at $250, and (d) the auction terminates after 6 hours and funds are transferred. With these rules, John and the potential buyers can securely reach a consensus on the final price of the tablet. Fig. 2 illustrates the operation of this sample smart contract once it is triggered.

Let us assume that of all network participants, only Jane, Jeff, and Jason are interested in purchasing John's tablet. They would use the unique address assigned to John's smart contract to retrieve it from the network. Once the auction time begins, these participants will proceed to submit their bids. Suppose Jane bids $370, Jeff bids $450 and Jason bids $320. According to the predetermined smart contract rules, the auction will remain open until all bids have been received, or until the bid-collection time runs out. Next, the smart contract will automatically select and announce the highest bidder as the winner. Finally, the funds will be transferred from the winner to John. Furthermore, all transaction details of the executed smart contract would be recorded in the blockchain for future reference. In this case as Jeff is the highest bidder, he 'wins' the transaction and will buy John's tablet at $450. The smart contract will then transfer the $450 from Jeff to John. Hence, the seller (i.e. John) and the buyers (i.e. Jane, Jeff, and Jason) have reached an agreement on the final price of the tablet as $450 by using the smart contract.

## 3. Applications of blockchain technologies in power distribution systems

The application of blockchain technologies to power distribution systems has the potential to enable systems with extensive interconnection, intelligent decision-making, real-time interaction, and open data sharing (Zhu, 2019). This section summarizes multiple different applications of blockchain technologies to power distribution systems and provides examples of successful commercial implementation, refer to Fig. 3.

### *3.1. Transactive energy*

The development of smart grid technologies in power distribution systems enables bidirectional energy and data flows: conventional consumers can now act as prosumers to participate in energy trading. The introduction of blockchain can help prosumers participate in a transactive energy markets efficiently, automatically, and without the need for a central governing authority. Therefore, transactive energy is often considered to be one of the most attractive applications of blockchain. There are several pilot projects for blockchain-based transactive energy management. In this section, we further discuss different ways in which blockchain technologies can facilitate transactive energy management.

#### *3.1.1. Cryptocurrencies and tokens in energy transactions*

With the development of bitcoin, cryptocurrencies and digital tokens became one of the most popular applications of blockchain technologies. Cryptocurrencies and digital tokens can monetize assets (Andoni et al., 2019) and can thus be used as rewards to incentivize

**Table 1**
Summary of blockchain types and their characteristics.

| Characteristics | Public | Private | Consortium |
|---|---|---|---|
| Participants and security | ● Accessible to all participants<br>● Participants are anonymous and may be malicious<br>● Decentralized | ● Accessible to trusted participants<br>● Participants are known and trusted<br>● Centralized | ● Accessible to trusted participants<br>● Participants are known and trusted<br>● Partially centralized |
| Consensus algorithms | ● PoS or PoW<br>● Slow (could be several minutes) | ● PoA<br>● Faster (only seconds) | ● Integration of PoS and PoA<br>● Fast (only seconds) |
| Energy consumption | ● High energy consumption | ● Low energy consumption | ● Low energy consumption |
| Applications | ● Public transactions or projects (e.g. Bitcoin) | ● Projects that require control of the data (e.g. supply chain management) | ● Projects that require a high level of trust (e.g. transactions among companies) |

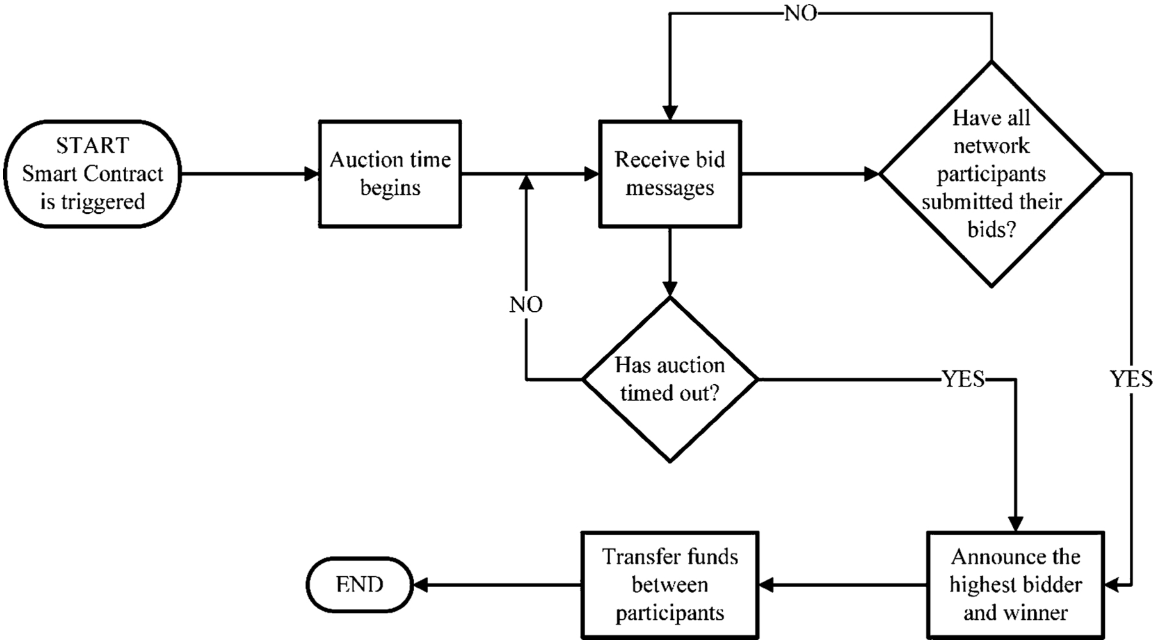

**Fig. 2.** Operation of sample smart contract.

prosumers' participation in the energy market. For instance, surplus energy could be tokenized and then exchanged for either fiat currency or cryptocurrencies. Smart contracts can be used here to automatically exchange the surplus energy for digital tokens and execute payments between users. These self-executable blockchain-enabled solutions can reduce money transfer costs and increase system security. Some examples of cryptocurrencies and tokens in the energy market include SolarCoin, EverGreenCoin, EcoCoin, EECoin, NRGcoin, etc (Andoni et al., 2019). Furthermore, cryptocurrencies and tokens can also be used as instruments for granting rewards for energy efficiency and greenhouse gas reduction measures. For instance, Energi Mine uses smart contracts to reward consumers with tokens for successfully reducing their energy consumption (EnergiMine, 2017).

### *3.1.2. Peer-to-peer energy trading*

In conventional distribution systems, prosumers can only participate in the energy market through third-party entities, which can result in high operational and regulatory costs (Mollah et al., 2020). Integrating blockchain technology into the energy market will eliminate the need for these third-party entities and the conventional energy market will be transformed into a peer-to-peer energy trading market. Smart contracts can be used here for automatic real-time market clearing and market settlement which can speed up transactions and reduce transaction costs. There are several pilot projects for peer-to-peer energy trading based on the blockchain in (LO3 Energy, 2019). In Brooklyn, New York, two firms called LO3 Energy and Consensys worked together and successfully developed a blockchain-enabled microgrid system that allows residents to carry out decentralized peer-to-peer transactions with their neighbors (Xie et al., 2019; LO3 Energy, 2019).

### *3.1.3. Carbon trading*

Current research has focused on the development of blockchain technologies for automatic carbon trading. Carbon trading is the

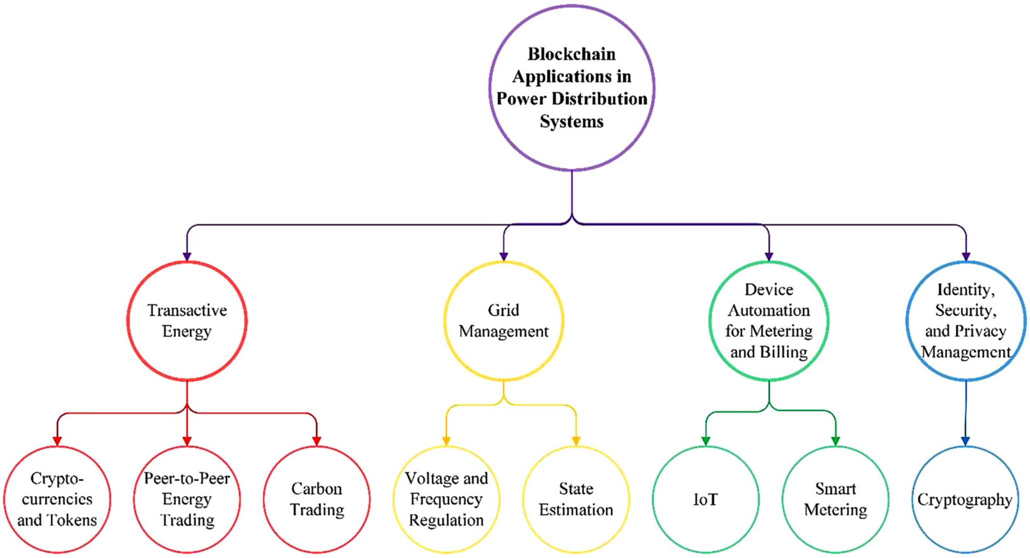

**Fig. 3.** Blockchain applications in power distribution systems.

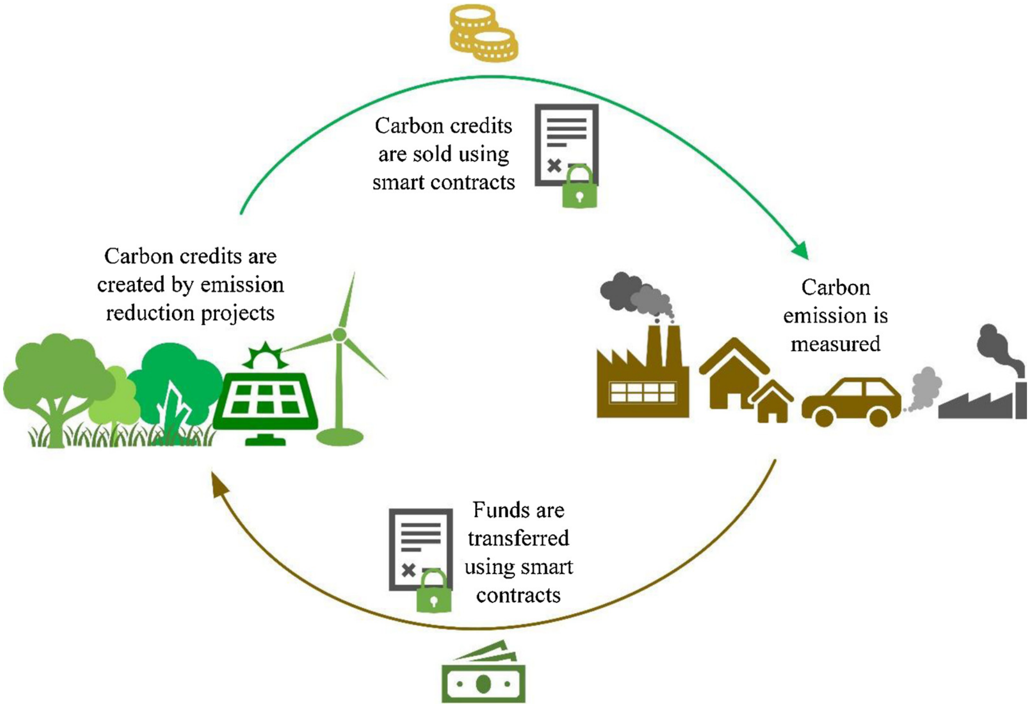

**Fig. 4.** Blockchain-enabled carbon trading.

assessing, storage, exchange, and management of carbon assets such as carbon credits (Andoni et al., 2019; Pan et al., 2019). Carbon credits are assets that entitle the owner with the right to emit certain amounts of greenhouse gases. Using smart contracts, blockchain-enabled power systems can facilitate global markets for carbon assets, see Fig. 4. First, carbon credits are created through emission reduction projects. Then, the carbon emitters need to measure their carbon emission and purchase equivalent carbon credits from the emission reduction projects using smart contracts. In addition, these carbon emitters also send money to fund global emission reduction projects using smart contracts. Applying blockchain technologies to carbon trading allows for secure, reliable, and efficient carbon transactions. Nasdaq was the first global stock exchange to explore the application of blockchain technologies to carbon trading (Andoni et al., 2019). In addition, there are other pilot projects currently under development to further explore this field. For instance, IBM has partnered with Energy-Blockchain Labs to create a decentralized carbon credit management platform to reduce the total cost of China's national carbon market by 30 % (IBM, 2018). In addition, the application of blockchain to carbon trading has the potential to increase consumer participation in the transactive energy market.

### 3.2. Grid management

Grid management refers to the system's ability to monitor, manage, and control devices that facilitate grid operations (e.g., voltage and frequency regulation, state estimation). Applying blockchain technologies to grid management can decentralize and automate the monitoring and control of grid devices (e.g. DERs, voltage and frequency regulators). Blockchain technologies can create a rapid self-healing grid by embedding grid devices with smart contracts. The smart contracts will automatically enable real-time identification and resolution of anomalies in grid operation. For instance, voltage and frequency control devices embedded with smart contracts can automatically adjust voltage and frequency values. In addition, blockchains in grid management can facilitate system transparency by reading and sharing state estimation data with network participants. The increased system transparency improves the reliability and resiliency of grid management solutions (Banks et al., 2019). To demonstrate blockchain benefits in grid management, PONTON successfully developed a software, called Gridchain, which uses blockchain technologies to simulate future processes for real-time grid management (EnerChain, 2020). The designed system uses blockchain technologies to estimate and provide effective grid management solutions.

### 3.3. Device automation for metering and billing

Internet of Things (IoT) technology allows for fast and efficient communication between devices within the system. Metering and billing services can be enhanced by adopting IoT technology in the distribution grid, since this would allow devices to communicate with each other in real-time. However, existing IoT platforms need to become more decentralized and secure in order to make them more scalable and sustainable (Christidis and Devetsikiotis, 2016). Blockchain technologies offer a secure peer-to-peer architecture that can facilitate the adoption of IoT technology for metering and billing. Combined with blockchain technologies, IoT platforms can work together with metering infrastructure to provide automated billing services for all electricity consumers in order to reduce the overall administrative cost (Andoni et al., 2019). Fig. 5 shows how IoT and blockchains can function together. We assume each participant embeds smart contracts into the smart meters. For instance, a smart home wants to purchase energy from a wind farm. The smart home uses its smart meters to measure and send the energy consumption information to the wind farm. Then, the smart meters of the wind farms will read and interpret the information received from the smart home. If the predetermined smart contract rules are met (e.g., the generation cost is less than the energy price offered by the smart home), the smart meters on the wind farm will automatically sell energy to the smart home.

Existing ongoing projects are demonstrating the potential of blockchain technologies for energy metering and billing. For example, Pylon Network's smart meter, called Klenergy Metron, can trace and automatically record energy produced and consumed (Pylon Network, 2018). Klenergy Metron uses blockchain technologies to facilitate smart metering solutions for grid enhancement and management. Another example is from Germany, where an entity called Slock is developing an IoT and blockchain applications platform for smart metering. This

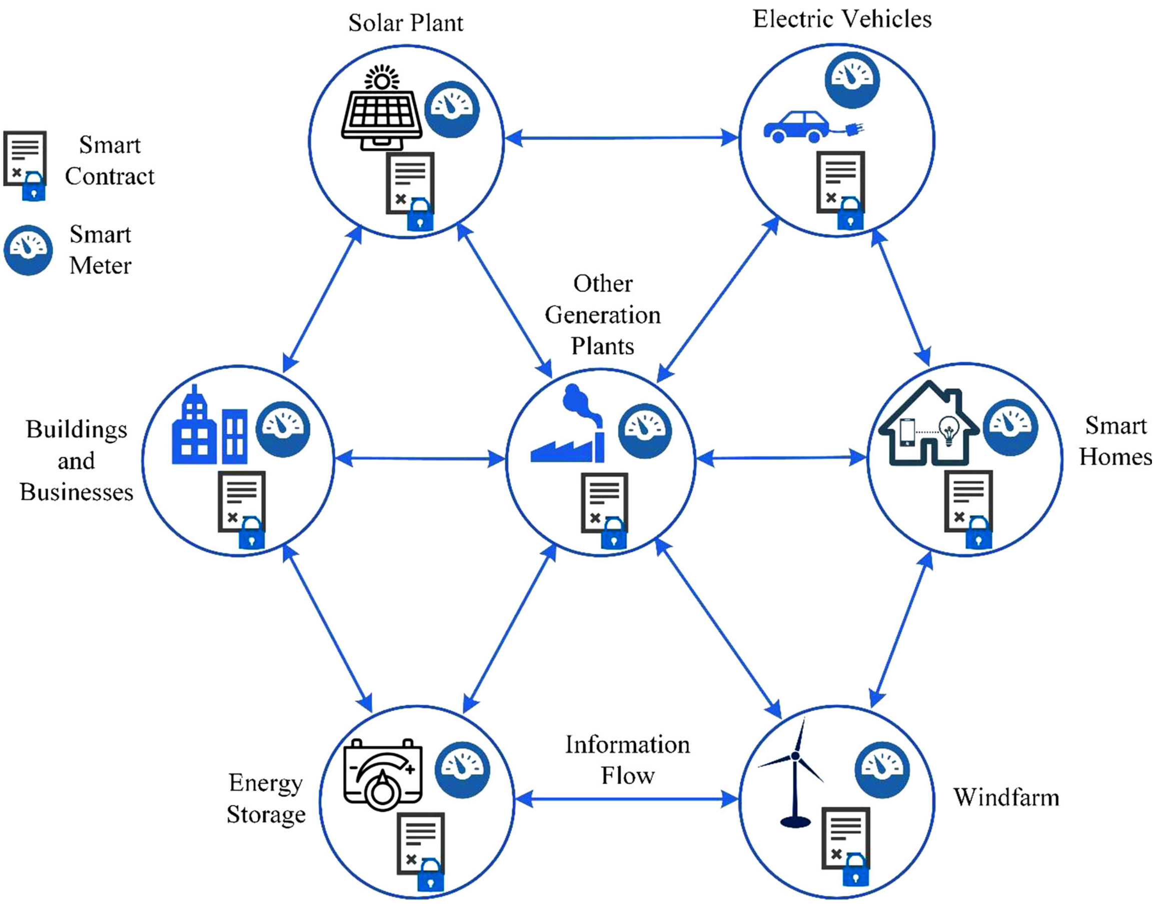

**Fig. 5.** IoT in blockchain systems.

platform is called the Universal Sharing Network, and its goal is to employ IoT and smart contract solutions to smart devices and energy transactions (Andoni et al., 2019; Tual, 2017).

### 3.4. Identity, security, and privacy management

With the advent of grid modernization, there is an increased level of communication between the energy generation, distribution, and consumption layers of the grid. This leaves the system more vulnerable to malicious attacks: by using the smart meters present in smart grids, malicious entities can attempt to analyze the electricity consumption profile of network participants to access private consumer information (Alladi et al., 2019). The cyber-secure characteristics of blockchains will guarantee a safe and credible information flow between all the involved participants. The information will be protected by cryptographic techniques (e.g., encryption) with the introduction of blockchain. As is illustrated in Fig. 6, blockchains protect participants' data by resisting attackers who seek to access the network. The system is further protected from malicious entities and cyberattacks by using smart contracts to monitor data and then intelligently make decisions regarding system security. Hence, blockchains can be applied to enforce system abnormality control measures (Alladi et al., 2019) in order to protect the private information of the power network participants.

## 4. Challenges of blockchain applications in power distribution systems

Although the application of blockchain technologies to grid modernization has successfully passed the proof-of-concept stage (Andoni et al., 2019), there are a few challenges preventing blockchains from being applied in practice. These challenges should be addressed and improved for implementing blockchain technologies in power distribution systems. We introduce these challenges in detail in the following section.

### 4.1. Implementation costs

A significant challenge for applying blockchain technology in practice is its high implementation cost (Andoni et al., 2019). The implementation of blockchain requires updating the existing data storage and communication systems. This could be an extremely expensive venture since many devices may need to be replaced with their blockchain-enabled counterparts. In addition to the high hardware costs, blockchain processes (e.g., data validation, verification, and storage) are very energy-intensive, leading to high energy costs. Hence, methods for reducing the costs of blockchain technologies are still under research to hasten its complete adoption in the power distribution system.

### 4.2. Consumer participation

The introduction of blockchain to transactive energy markets eliminates the need for a central authority to approve transactions and makes decentralized energy transactions possible. In other words, participants can trade energy with each other without a market operator. Unfortunately, the participants may lack the knowledge to submit reasonable bids and offers in a dynamic energy market. In addition, the participants may not be familiar with blockchain technologies and do not know how to make proper use of blockchains. Therefore, one of the key barriers to blockchain relates to the high costs associated with educating participants on their role in the decentralized market. The use of smart contracts could be an effective solution towards the above challenge by simplifying the procedures for energy

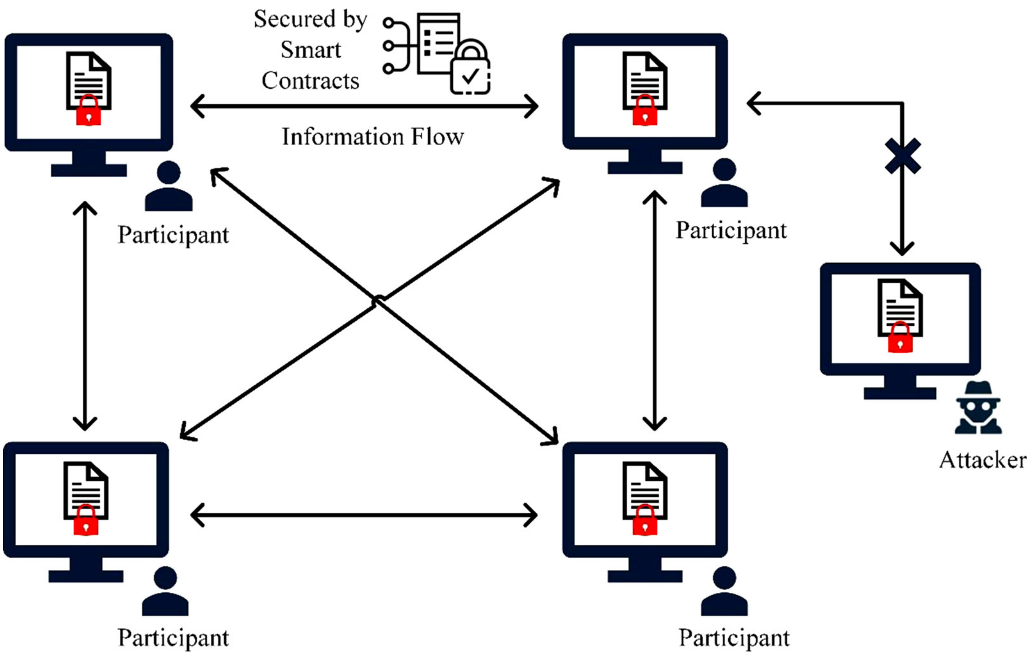

**Fig. 6.** Cyber-secure characteristics of blockchains.

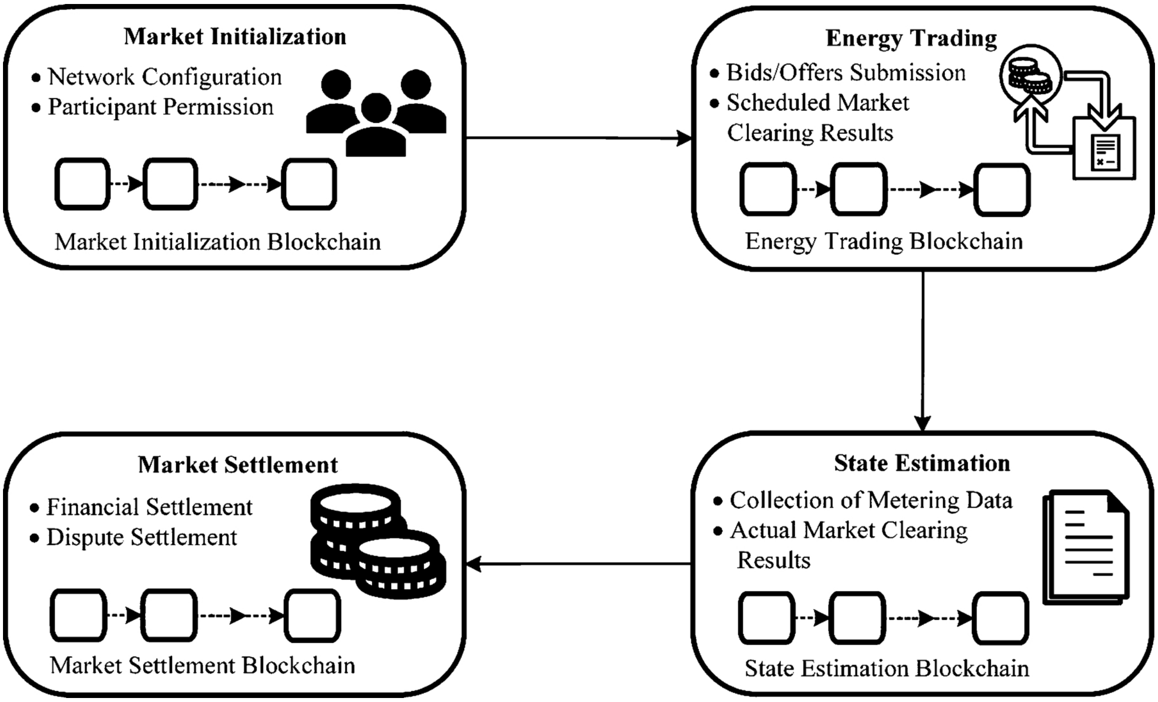

**Fig. 7.** Proposed framework for blockchain-enabled transactive energy management.

transactions. Artificial Intelligence (AI) technology is also being considered as a method for simplifying energy transactions. AI enabled blockchain solutions can enhance consumer participation by further automating the exchange of energy in a decentralized manner (Salah et al., 2019).

### 4.3. Data-processing constraints

The application of blockchain technologies introduces a higher demand on communication and data processing systems. For example, in the case of transactive energy, many participants simultaneously trade energy every second of every day. Hence, the communication system needs to be updated to ensure that it is robust enough to enable flexible communication flow among participants. In addition, since energy transactions are dynamic and pricing continues to change in real-time, the data processing system is expected to instantly process large quantities of transactions. Several techniques such as *sharding* (Mollah et al., 2020) and *sidechains* (Xie et al., 2019) are being considered as methods for improving blockchain communication and data processing systems. Sharding is the process of partitioning blockchains into separate shards, with each shard overseeing its own data management. Sidechains can be used to store the data in another side-blockchain, thereby reducing the data-flow burden on the main blockchain.

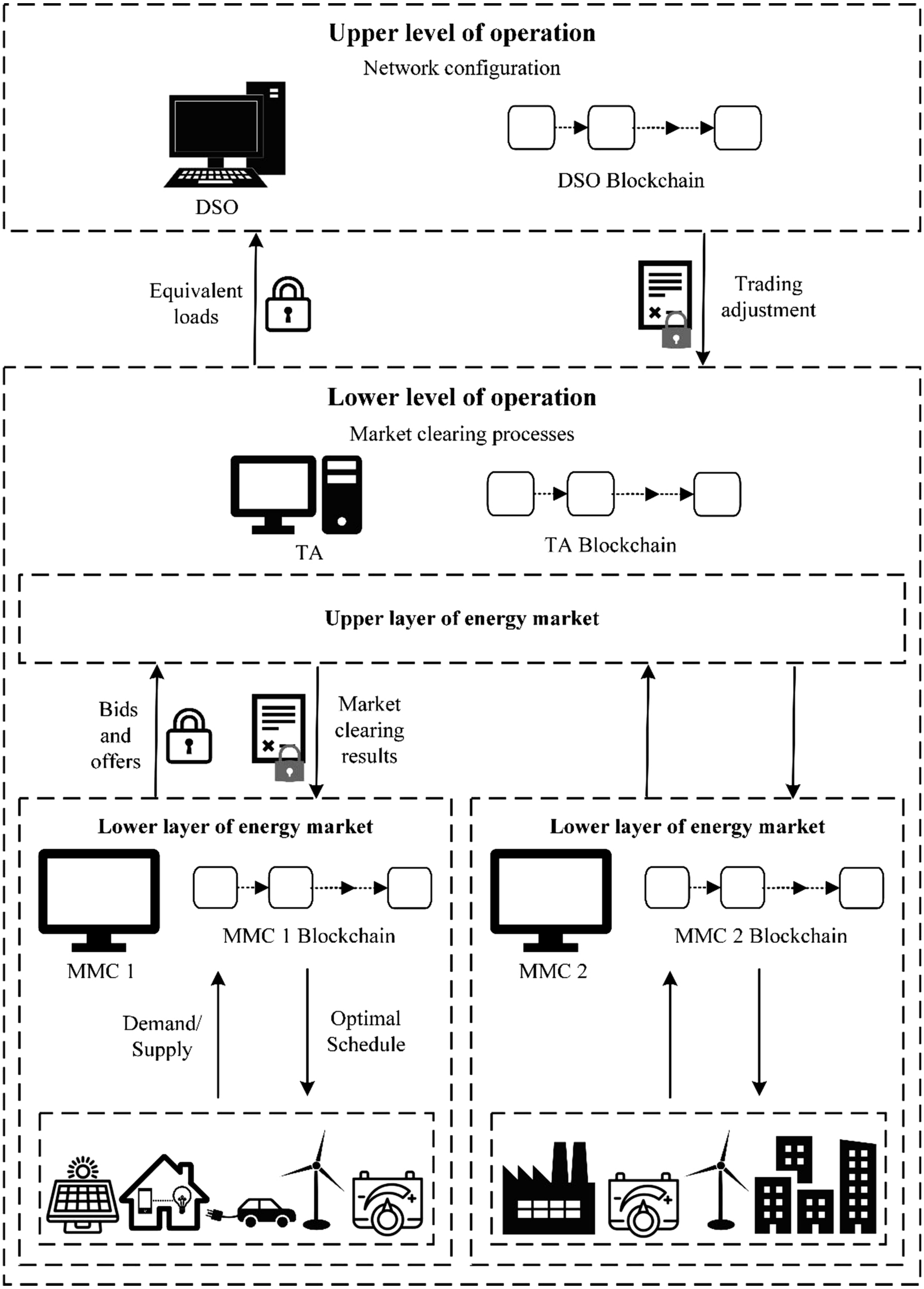

**Fig. 8.** Proposed architecture for energy trading in networked IIT-Bronzeville microgrids.

### 4.4. *Legal support and regulations*

The current laws and regulations are designed to support transactions on conventional power systems and are not able to handle large scale peer-to-peer transactions. A simple fix to this problem would be to adjust the existing policies to accommodate these new transactions. Smart contracts can be developed to ensure that transactions in power distribution systems comply with the law and updated regulations, consumer data protection, maximization of network assets, etc.

## 5. Case study: transactive energy trading in networked microgrids

In this section, we consider blockchain-enabled decentralized energy trading frameworks for networked microgrids. A detailed analysis of these projects can be found in (Li et al., 2019). The proposed framework utilizes blockchain technologies to secure and optimize the financial and physical operations of power distribution systems. Hence, a set of interoperable blockchains embedded with self-executable smart contracts was developed to securely manage energy and financial flows among transacting networked microgrids (Li et al., 2019). As shown in Fig. 7, the proposed framework is divided into four stages and utilizes four permissioned blockchains. The four stages were identified as the market initialization, energy trading, state estimation, and market settlement stages respectively. Note that each of these stages possesses its individual blockchain that stores information and can interoperate with the others.

In the market initialization stage, the distributed system operator (DSO) handles the network configuration. The DSO also manages participant permission by weeding out those that are not eligible to participate in the transaction. In the energy trading stage, the network participants submit their bids and offers for market clearing. In the state estimation stage, the actual market clearing results (e.g., the generation and consumption of prosumers) are obtained using real-time metering data collected from devices in the network. Finally, in the market settlement stage, all previously established smart contracts are automatically executed according to the market clearing results, and financial settlements are made. In addition, the market settlement blockchain will determine each participant's payment or revenue by collecting the scheduled and actual market clearing results from the energy trading and state estimation blockchains, respectively. This proposed blockchain-based framework for energy trading is expected to lay the foundations for the optimization of the energy market.

A further example of blockchain-based peer-to-peer energy trading can be found in the Chicago metropolitan area. Here, a two-layer blockchain-enabled energy trading market was proposed and tested on the models of both the IIT campus and Bronzeville neighborhood microgrids, since they are neighboring microgrids and are thus able to form a network. The IIT microgrid is operated by Illinois Institute of Technology, while the Bronzeville microgrid is operated by ComEd, the sole electric services provider in Chicago and throughout northern Illinois. This project proposed a two-level operation process, the DSO at the upper level and the transactive aggregator (TA) at the lower level. Fig. 8 illustrates the proposed blockchain-based architecture for peer-to-peer energy trading in the networked IIT-Bronzeville microgrid model.

In the upper level of operation, the TA clears the transactive energy market and submits the market clearing results to the DSO. For privacy concerns, each microgrid is regarded as an equivalent load or generator. Then, DSO manages the optimization and security of the network configuration using optimal power flow methods. More specifically, the DSO sends a trading adjustment request to the TA if network security is violated. The TA will revise the market clearing results according to the trading adjustment request. The lower level of the energy trading operation is further split into two layers to accommodate the individual roles of the TA and microgrid master controllers (MMCs). In the lower level of operation, the TA works closely with the MMCs to manage a two-layer transactive energy market. Here, the MMC serves as an intermediary between the buildings and TA and is expected to aggregately manage the DERs and loads of all buildings. Based on individual building demand/supply, the MMCs submit the bids/offers to the TA and the bidding submission is authorized by transferring the corresponding data block to the TA blockchain. The MMCs then determine the optimal schedule of each building.

## 6. Conclusion

In this paper, we discuss the application of blockchain technologies as a grid modernization strategy, and deeply examine its benefits and challenges. The versatility of blockchain technologies enables it to be applied to multiple areas of power distribution systems, ranging from peer-to-peer energy trading to asset management. Major advantages of blockchain technologies include its ability to reduce transactional costs, improve system resilience, and enhance system security. Blockchain technologies also enhance system transparency, guarantee accountability, preserve privacy, and enable the development of new business models and marketplaces. As blockchain technologies mature, they are bound to gain increased scalability and incur lower operational costs. This growth will make blockchain technologies even more vital to the development of optimal decentralized modes of operation and transactions in our growing energy industry.

## Declaration of Competing Interest

The authors report no declarations of interest.

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