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Review of Blockchain Potential Applications in the Electricity Sector and Challenges for Large Scale Adoption

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ABSTRACT Blockchain technology applications in the electricity sector are getting considerable attention from both academia and industry. It is expected that blockchain will play an important role in the transition to the smart grid. The blockchain applications in the electricity sector can be classified to optimizing existing processes like metering and billing or grid management and using blockchain for emerging applications such as creating new platforms for value exchange like peer-to-peer (P2P) energy trading. This paper briefly introduces the fundamentals of blockchain technology, such as different types of blockchain networks and consensus mechanisms, in addition to introducing a few blockchain platforms that are widely used in current studies, projects, and startups or may have future potential in the electricity sector applications. The contribution of this paper is to provide a review of potential applications of blockchain in many electricity sector use cases, and they are categorized into eight categories such as P2P energy trading, wholesale markets, retail markets, metering and billing, trading of renewable energy certificates (RECs) and carbon credits, electric mobility, enhancement of power system cyber security, investments in renewable energy sources (RESs), and power system operation and management. Moreover, examples of research studies, pilot projects, industrial projects, startups, or companies investigating the blockchain capabilities at each potential application are introduced. Furthermore, the studies presented in each use case are compared to clarify and highlight the blockchain functions and involved actors. Finally, the paper discusses the challenges that blockchain technology is facing that obstruct large-scale adoption in different sectors and in the electricity sector specifically and potential solutions to these challenges that are being developed.

INDEX TERMS Blockchain applications, distributed ledger technologies, distributed ledger technologies applications, peer-to-peer energy trading, local electricity markets, electric vehicles, smart grid.

I. INTRODUCTION

There are fast developments in electric power systems. The share of unpredictable and intermittent RESs is increasing rapidly. In addition, large developments are executed in distribution networks that encounter significant changes. There will be more engagement of the demand-side by deploying local generation, local storage, electric vehicles, controllable loads, and smart metering infrastructure with a change from centralized to decentralized grid structure. It will change from a one-way flow of energy, communication, and transactions to two ways with a large number of participants (i.e., millions or billions of devices). These significant changes introduce challenges in the operation, management, control, economics, and security of power systems [1]–[3]. Considerable investments are required for sustainable and secure future power systems. With this evolution, central management and control of the power system is complex and inefficient [4]. Therefore, decentralized management systems should be developed for optimal operation and control of distribution networks. Blockchain as a decentralized (i.e., distributed) technology that removes or reduces central management seems a promising choice to tackle some challenges in decentralized future power systems [5]. It is expected that blockchain could play an important role as enabling technology in the transition from centralized power systems to decentralized power systems [6]. It has the potential to increase transparency and trust between different

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stakeholders, enhance data security, minimize transaction costs, automate processes, and facilitate the active participation of small consumers and prosumers in the smart grid. Moreover, it can facilitate investment in distributed RESs and foster their adoption.

A large number of research studies investigated the potential applications of blockchain in different research areas in the electricity sector. Also, several startups, companies, utilities, and system operators invested in blockchain use cases in the electricity sector to investigate its potential benefits in sustainable future power systems. The majority of use cases focused on P2P energy trading in a district where the blockchain-based platform can match consumers and prosumers bids and enable trading of energy between neighbors and handle the financial transactions between participants at low cost. Blockchain could be used to optimize the operation of wholesale and retail markets by eliminating many intermediaries, decreasing manual and time-consuming processes, and enabling low-cost and fast transactions between market participants. Blockchain could make metering and billing processes automatic, more transparent, more efficient, and with less administrative costs. Blockchain could be used to automate the issuance of RECs by integrating blockchain and smart metering. It could be used to create a market for RECs and carbon credits trading. Blockchain could minimize the range anxiety and foster electric vehicles (EVs) adoption by facilitating access to private EV chargers. Using blockchain, EV owners can share their private EV chargers with others and receive immediate payment while preserving EV owner privacy. The cybersecurity of power systems can be enhanced using blockchain technology at all power system levels (i.e., generation, transmission, and distribution). Blockchain can increase investments in RESs by enabling co-ownership of renewable energy assets and automatically divides revenues between investors. Blockchain can be used for enhancing the operation and management of future power systems with a high share of distributed energy resources (DERs) [7], [8].

Considering academia and industry's massive interest in blockchain-based solutions in the electricity sector, many studies reviewed the work being done. In [9], four applications of blockchain in the electricity sector were discussed, and the authors focused on reviewing academic research studies. Reference [10] reviewed five applications of blockchain in the electricity sector, focusing on research articles, and also introduced a few blockchain platforms developed for energy sector applications. Another study [11] reviewed the research studies investigating blockchain use cases in five use cases focusing on providing technical details. Furthermore, a few startups were briefly discussed in this study. Reference [12] provided details about blockchain technology and presented 140 projects and startups that are using blockchain-based solutions in different use cases in the energy sector. Reference [13] discussed four blockchain applications in the energy sector and analyzed how blockchain can be used to reform china's energy sector. Another study focused on blockchain-based energy trading only due to the large interest in this use case from academia and industry [14]. Moreover, few reports from the industry were published focusing on presenting the companies engaged in blockchain-based solutions for the electricity sector use cases [8], [15]. This review article presents eight blockchain-based use cases in the electricity sector. Examples from research studies, industrial pilot projects, trials, and startups are presented. The blockchain added value and functions at each use case are highlighted. Additionally, this study discusses the challenges and barriers for wide adoption of blockchain in many electricity sector applications.

The major contributions of this paper can be summarized in the following points:

- Briefly introduce the blockchain technology (i.e., consensus mechanisms, different types of blockchain networks, widely used blockchain platforms, and the functions of blockchain smart contracts in electricity sector applications) to enable the reader with no background in blockchain technology to understand the rest of the paper.
- Present potential applications of blockchain technology in the electricity sector that received attention from both the research community and industry.
- The applications are categorized into eight categories such as P2P energy trading, wholesale markets, retail markets, metering and billing, trading of RECs and carbon credits, electric mobility, enhancement of power system cyber security, investments in RESs, and power system operation and management.
- Examples of research studies, pilot projects, industrial projects, startups, and companies that study the blockchain capabilities at each potential application are introduced.
- The studies presented at each application are compared to clarify the involved actors and blockchain functions because it is usually unclear what is the functions of blockchain in different applications.
- Present and discuss evaluation criteria for suitability of blockchain technology to an application to clarify that blockchain may not be suitable for many applications.
- A comprehensive discussion on the challenges that blockchain technology faces that obstruct large-scale adoption in different sectors and the electricity sector specifically and potential solutions to these challenges. The discussed challenges clarify many research gaps that need more studies and research.

The paper is organized as follows: Section II briefly presents a general background about blockchain technology, consensus algorithms, blockchain classification, blockchain platforms, and smart contracts function in the electricity sector applications. Section III introduces potential applications of blockchain technology in the electricity sector. In this section, for each potential application, the effort of academic institutions in the form of research papers and industry (i.e., companies, utilities, system operators, and startups)

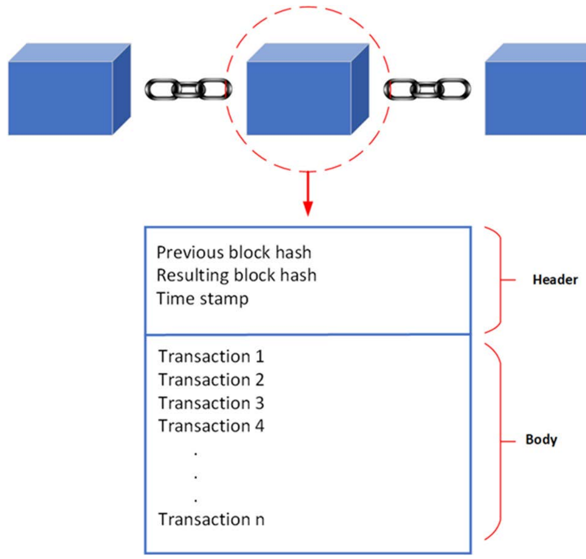

FIGURE 1. Blockchain general structure.

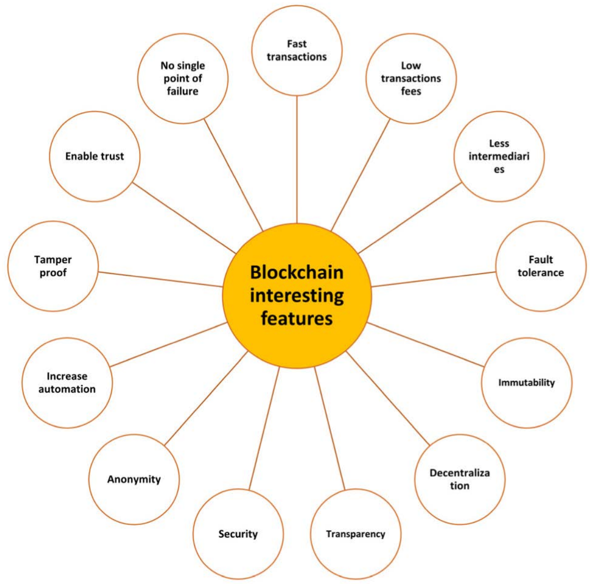

FIGURE 2. Blockchain technology main features.

studies, pilot projects, and real applications are presented. Section IV presents a summary and comparison of research studies, projects, and startups discussed in section III. Section V discusses the challenges of blockchain technology and potential solutions that are being studied. Finally, conclusions are presented in section VI.

II. BLOCKCHAIN BASICS AND GENERAL BACKGROUND

Blockchain is a P2P technology that enables distributed data storage, data sharing, and computing between network participants. Blockchain is a chain of blocks containing data, information, or transactions. Blocks are connected using cryptography to ensure security and attack resistance. Blockchain is a decentralized database usually referred to as a distributed ledger, distributed on the computers (i.e., nodes) which verify transactions. Each participant or node has a copy of all verified transactions stored on his computer. This eliminates the single point of failure issue encountered in central databases, which may fail due to technical reasons or cyber-attacks [16]. Blockchain is immutable, and once a block is created and added to the chain it is extremely difficult to be modified or removed [16]. No intermediaries or fewer intermediaries are involved, which enables fast transactions with cheap or no transaction fees. Transparency is a big advantage of blockchain because participants can see all changes. Blockchain is open, and everybody can participate (i.e., in the case of public blockchain).

As shown in Fig. 1, each block in the blockchain consists of a block header and a block body. The block header has the previous block hash to connect the current block to the previous one, the current block hash, and a timestamp which refers to the time of block creation. The block body contains transactions or stored information. Each transaction contains the sender's public key, the receiver's public key, the amount to be transferred, time, etc. Blockchain was called the internet of value because it enables value (i.e., money or assets) transactions without intermediaries, which is not possible on the traditional internet (i.e., the internet of information). It was called the trust protocol because it enables peers who do not know or trust each other to do business together with no trusted intermediary involved [17]. Fig. 2 presents a list of the main features of blockchain technology that attract many sectors to study its possible applications.

A. CONSENSUS ALGORITHMS

Traditionally, third parties like banks are the responsible entities for verifying and managing accounts balance and transactions. In opposition, in blockchain (i.e., public blockchain) verification process is the responsibility of all blockchain participants because each one has an updated copy of the blockchain. The process of verifying transactions and agreement on transaction data correctness by nodes is done by consensus algorithms. After the transactions in a new block are verified and the consensus is reached, the block is added to the blockchain. In general, consensus refers to the process of reaching a common agreement between participants of distributed multi-agent system. Consensus guarantee operations correctness even with the existence of malicious or faulty individuals. There are many consensus algorithms used in blockchains, such as proof of work (PoW), proof of stake (PoS), proof of authority (PoAu), and practical byzantine fault tolerance (PBFT), among others [18], [19]. They have different properties, strengths, and weaknesses which make them suitable for various applications. The algorithm used to reach consensus defines the blockchain performance characteristics like resources needed (i.e., computational power and electricity consumption), security, transaction speed, and scalability. Therefore, many consensus mechanisms were developed and are being developed to tackle the weaknesses of previous mechanisms and to achieve the requirements of different applications.

1) PROOF OF WORK (POW)

PoW name comes from the need for computation power work done by miners to solve a cryptographic puzzle and request the right to create the next block. The miner who solves the puzzle first gets rewarded with newly created coins and the created block transaction fees. This process is called mining and is done by computers with high computational power with no human intervention. PoW is the most widely used consensus algorithm and is used by Bitcoin, Ethereum, and other public blockchains. The high computational power needed in PoW makes it suitable for public blockchains to resist attacks. The attacker must have more than 51% of the blockchain network power in order to control it. However, PoW is energy-intensive and needs high computational power [20], [21]. Also, blockchain platforms that use PoW consensus have a slow transaction validation speed, 10 minutes for Bitcoin and 15 seconds for Ethereum to add a new block in the blockchain. Moreover, the number of transactions processed per second is extremely small. Therefore, Ethereum will change soon to PoS, which is more efficient [22].

2) PROOF OF STAKE (POS)

PoS has no miners but depends on the stake (i.e., coins) participants offer or deposit. Only participants who deposit stakes can participate in consensus. The higher the stake participant offers, the higher the probability of being selected to create the next block in the blockchain. The reward for the block creator is only the transaction fees, and no new coins are created when a new block is added to the chain. If any participant behaves maliciously, he will lose his stake, which makes PoS suitable for permissionless networks. PoS is simpler and has lower computational complexity and operating cost than PoW. However, the attack cost decreases with the decrease in computational complexity, which makes it more vulnerable to attacks than PoW. PoS is still immature compared to PoW and needs more development and investigation of its scalability. PoS is used by Cardano [23], and Ethereum intends to use it instead of PoW due to its issues [22].

3) PROOF OF AUTHORITY (POAU)

For PoAu consensus mechanism, there is a number of approved (i.e., trusted) participants who are responsible for verifying transactions and collecting them into a block. There is no need for solving computational puzzle or stake offers. PoAu does not need communication between trusted nodes and requires small resources (i.e., resources efficient). However, the dependence on trusted nodes in this consensus algorithm decreases the trustless characteristic of the network. Consortium and private blockchains usually use PoAu consensus mechanism. PoAu has fast verification time and consensus, but it is more centralized, which makes it more vulnerable to attacks compared to other consensus mechanisms such as PoW and PoS. PoAu is used in Energy Web Chain (EWC), a test network developed by Energy Web Foundation (EWF) for energy sector applications.

4) PRACTICAL BYZANTINE FAULT TOLERANCE (PBFT)

Byzantine Fault Tolerance algorithms deal with the byzantine generals' problem. The problem is for a group of generals leading different army parts that are coordinating to take a decision for the army to attack a citadel or not. The challenge of this problem is that the message of each general can be lost without notification to the sender or receiver, and there is a possibility of a few generals being a traitor and does not send messages or send false messages. Therefore, there is a need to make sure that honest generals make the decision without being affected by traitors [24]. In the blockchain, the generals are equivalent to nodes, and deciding after coordination is equivalent to reaching a consensus. Then, the PBFT algorithm was proposed in [25]. It was developed to solve issues in PoW, such as energy consumption and latency. This mechanism requires a large number of messages to reach a consensus. PBFT consensus has a primary and secondary replica. The secondary is checking the primary decisions correctness and takes actions if needed, such as switching to a new primary. PBFT requires at least 2/3 of blockchain network nodes to behave honestly. PBFT is widely used in blockchain networks, especially with trusted validators (i.e., private blockchain), and is used by the Hyperledger blockchain platform. A comparison of the presented consensus mechanisms is given in Table 1.

B. PUBLIC, PRIVATE, AND CONSORTIUM BLOCKCHAIN

Different projects, companies, or applications have different requirements and needs. Some applications need an open system allowing anyone to participate such as cryptocurrencies. In contrast, other applications require control of the data and access to its system by only authorized persons. Therefore, there are different types of blockchain network management, and they can be classified into public, private, and consortium [26], [27]. This classification is based on who is allowed to access the blockchain network.

A public blockchain is a permissionless network that allows anyone to join the blockchain network. All participants have the right to make transactions and participate in consensus for block creation. Also, all blockchain participants can view transactions, but the identities are anonymous. Public blockchain has a limitation on the number of transactions per second processed (i.e., low throughput), but it can scale to a large number of nodes. There is much research now to develop methods to solve this issue like sharding, off chains, etc. [28], [29]. However, implementing these solutions while preserving public blockchain decentralization and security is a challenge. Bitcoin and Ethereum are examples of the public blockchain.

A private blockchain is a permissioned network that allows only authorized participants to view transactions and is controlled by one organization. Therefore, private blockchain provides more information privacy than public blockchain. A limited number of nodes work as miners, and they are responsible for validating transactions. Joining the blockchain is restricted to specific people such as

TABLE 1. Comparison between PoW, PoS, PoAu, and PBFT.

Features	PoW	PoS	PoAu	PBFT
Energy consumption	High	Low	Low	Low
Computation requirement	High	Low	Low	Low
Throughput	Low	High	High	High
Decentralization	High	High	Low	Low
Blockchain type	Permissionless	Permissionless and Permissioned	Permissioned	Permissioned
Security	High	High	Low	Low
Prone to forks	Yes	Yes	No	No
Applications	Cryptocurrencies	General	General	General
Platforms	Bitcoin and Ethereum	Ethereum (soon)	Energy Web Chain (EWC)	Hyperledger Fabric

organization employees. Usually, it has a simple and fast block creation and consensus process. Private blockchain allows a limited number of nodes but can process a large number of transactions per second due to instant transactions finality. The private blockchain is considered partially centralized due to the limited number of miners or nodes that maintain the network, which increases the possibility of tampering with the blockchain record. Hyperledger and Multichain are examples of private blockchain.

In between public and private blockchains comes consortium blockchain or hybrid blockchain, which is another type of permissioned network. In consortium blockchain, the ability of any node to access the network or get permission to make modifications is controlled by a group of organizations. In consortium blockchain, the consensus is reached by a preselected number of nodes. It allows only permissioned participants to join while keeping the public blockchain benefits. However, it is less decentralized than public blockchain. A few of the key features of public, private, and consortium blockchain are presented in Table 2.

C. DISTRIBUTED LEDGE TECHNOLOGY (DLT) PLATFORMS

The coming subsections present a few well-known blockchain platforms which have the largest number of applications. Platforms such as Ethereum and Hyperledger are the most used platforms in electricity sector applications. Most of the projects and startups use these open-source blockchain platforms in their systems, and few projects and startups have proprietary blockchain platforms that are developed for a certain application. A comparison between the discussed platforms is given in table 3 [30]–[32].

1) BITCOIN

In order to clarify the blockchain technology, the first and most successful blockchain use case will be explained, which is Bitcoin. Bitcoin platform was launched in 2009 after a few months of Satoshi Nakamoto's white paper publication. Bitcoin is a decentralized cryptocurrency or electronic payment system that allows fast and low-cost P2P transactions and payments worldwide. Bitcoin is a public blockchain network and uses the PoW consensus algorithm. In Bitcoin, no central authority such as the government or bank controls the network. The responsible people for verifying transactions, collecting them, and adding them to the new block are called miners [33]. The miners verify the identity of the sender and that he has the amount of money he wants to send or transact. Miners are competing to solve a mathematical problem (i.e., cryptographic puzzle), and the winner creates the new block and gets rewarded. The winning miner receives block transactions fees and receives a reward in the form of newly created Bitcoins. This reward was 50 Bitcoin/block when Bitcoin currency was created, and it halves every 210000 blocks (i.e., four years approximately). The reward was halved from 12.5 Bitcoin to 6.25 Bitcoin in May 2020 and will continue with this rate for approximately four years. Each number of transactions is grouped in a block and linked to the previous block in the chain and to the next block that will be created in 10 minutes. The miner must find the correct nonce and hash first and show PoW in order to win. It is not people who do the effort, but the software installed on computers with high computational power. Chance of winning

TABLE 2. Comparison of public, private, and consortium blockchain.

Features	Public	Consortium	Private
Architecture	Decentralized	Partially decentralized	Centralized
Node identities	Unknown	Known	Known
Nodes number	Unlimited	Limited	Limited
Throughput	Low	Medium	High
Transaction cost	High	Medium	Low
Permission	Permissionless	Permissioned	Permissioned
Immutability	Immutable	Partially immutable	Mutable
Transparency	High	Medium	Low
Security	High	Medium	Low
Prone to attacks	51% attack tolerance	33.33% attack tolerance	33.33% attack tolerance
Consensus	All miners	Set of nodes	One node
Consensus mechanism	PoW and PoS	PBFT	PoA and PBFT
Platforms	Bitcoin, Ethereum, IOTA	Hyperledger, EWC	Multichain and Hyperledger

increases with the increase in computational power. Small computers can also mine in the form of pools, which is a group of people working together to add their computational power [34].

The transaction execution in Bitcoin can be summarized in the following steps. First, a participant creates a transaction specifying the receiver address and money amount to be transferred. Second, the transaction will be transmitted to the network for verification and collected with other transactions in a new block every 10 minutes. Third, reach a consensus on the next block creation and add it to the chain. Last, the new blockchain is broadcasted to all distributed nodes. Each block has a hash for the previous block as a way to connect the new block to all the blockchain blocks. The hash of each block is unique, and it identifies the block content. If any data in the block change, the block hash will change [35]. Therefore, in order to make changes in any block, all the subsequent blocks must be changed, which needs a very large computational power. As a result, Bitcoin is resilient to tampering with transactions or data.

Bitcoin is pseudonymous; although all transactions can be seen by the public, the names of the sender and receiver are unknown. There is no need to provide any personal information such as name, email address, the phone number to have a Bitcoin wallet and make transactions. The transaction only contains their public keys, which work as their addresses. This gives participants control of their information and enhances their privacy. Although Bitcoin is announced as untraceable, it can be traced by the public key. Anyone can have many public and private keys that make a person's identity and data tracing very difficult. There are other solutions to prevent traceability, like hierarchical deterministic (HD) wallets. HD wallet uses an algorithm to create new public-private key pairs for every new transaction. A more sophisticated solution is zero-knowledge proofs.

2) ETHEREUM

Ethereum blockchain platform was launched in 2015. Ethereum was developed for public networks, but it can maintain private and consortium networks with a simple modification of its open-source code. Ethereum uses PoW consensus algorithm, but due to PoW issues, Ethereum will change to PoS, which is more efficient. Ethereum has its own cryptocurrency called Ethers, similar to Bitcoin. However, Ethereum added innovative features of smart contracts and decentralized applications (DApps). The smart contract is similar to traditional contracts, but it is digital (i.e., code) and stored in blockchain (i.e., distributed ledger). DApps are decentralized applications or blockchain-enabled websites that run on top of the blockchain. Smart contact and DApps can be written or programmed in Ethereum using solidity programming language and can run on Ethereum virtual machine (EVM). Smart contact is decentralized, which means no single entity controls them [36]. Moreover, Ethereum enables network participants to create their own tokens. Many startups are using Ethereum tokens to raise funding for their projects which is called Initial Coin Offerings (ICOs). Although Ethereum's innovative features made it the most suitable blockchain platform for developing blockchain-based solutions for many applications, it still has issues with cost efficiency and scalability. Ethereum is the most used platform in the electricity sector use cases due to the capabilities smart contracts provide [12].

3) ENERGY WEB FOUNDATION (EWF) PLATFORM

EWF was launched in early 2017 by Grid Singularity and Rocky Mountain Institute with ten other affiliates. In November 2017, EWF launched the first test network, Tobalaba. Then, they launched the second-generation test network, Volta. Finally, the Energy Web Chain (EWC) was launched in June 2019. EWC is a nonprofit, open-source blockchain infrastructure devoted to creating applications for the energy sector. It is a public, Ethereum-based blockchain at the user layer, with permissioned validators layer that uses PoAu consensus mechanism; and can be used to create private and consortium networks. This makes it scalable and can handle thousands of transactions per second, which makes it suitable for grid operators' needs. EWC is public, and any individual or company can make transactions through the network with no permission needed. The validators are large energy companies and market participants affiliated with EWF. This platform was developed to handle the unique needs of the energy sector in terms of operation, market, and regulation. EWF advises and convinces the energy sector participants by the value that blockchain can provide. Moreover, it implements proof of concepts and pilots to foster commercial deployment. Since EWF was launched, the number of affiliates increased until it passed 100 affiliates in March 2019, including blockchain developers, grid operators, and utilities. The current DApps developed by EWC focuses on energy trading, facilitating EVs charging, emission credits, and RECs issuance and trading [37].

4) HYPERLEDGER

Hyperledger is a project started in December 2015 by Linux Foundation with contributions from IBM, SAP Ariba, and Intel for open source blockchains. Hyperledger provides blockchain solutions for enterprises that do not prefer public blockchain, such as Ethereum, where the data can be seen by everyone, and mining fees must be paid in addition to scalability issues. They aim to develop blockchain platforms and frameworks that can foster the commercial adoption of blockchain. Hyperledger blockchain can enable easy, secure, and fast interaction between enterprises which is complex in the current structure for interaction between enterprises. Hyperledger can be used to create private and consortium networks, and it uses PBFT consensus algorithm. Hyperledger allows the creation of smart contracts, and they can be written in Golang, Java, and Javascript. The smart contract is called chaincode in the Hyperledger platform. There are many projects under Hyperledger that allow the creation of blockchain-based solutions for different industries, such as Hyperledger Fabric, Hyperledger IROHA, Hyperledger INDY, etc. [38].

5) IOTA

Internet of Things Application (IOTA) is a new DLT platform developed with the objective of solving issues of the current blockchain, such as scalability and high transaction fees. IOTA is a permissionless platform enabling scalable, secure, and feeless transactions. The IOTA uses the Tangle or Data Acyclic Graph (DAG) as it is called in mathematics, which is a different DLT from the blockchain. In opposition to the blockchain, the transactions are not grouped into blocks and connected to the chain, but each transaction is processed individually. Each participant must verify two previous transactions in order to perform his transaction, which will be verified by other participants, and so on. Therefore, IOTA can process an unlimited number of transactions per second. The Tangle allows continuous, simultaneous, asynchronous issuing of transactions. The structure of the Tangle can be seen in Fig. 3. Each square represents a transaction; the blue squares are the confirmed transactions and the green squares are the unconfirmed transaction (i.e., tips of the tangle). With this working principle where all participants have the same role and incentive, there are no fees for making transactions. Another advantage of the IOTA is that with the increase of activity in the tangle, the transactions will be confirmed faster because for each new transaction, two previous transactions must be confirmed, which solves the scalability issue. Moreover, the participant does not need to store the full Tangle network in order to create and verify transactions, only part of the Tangle should be stored, which reduces the storage requirement. IOTA has a token called MIOTA, which is a cryptocurrency that can be used for transactions. MIOTA was created to be used by IoT devices to enable them to make money transactions and data sending and receiving (i.e., M2M interaction) without any fees. IOTA uses a voting protocol called Fast Probabilistic Consensus (FPC) to reach a consensus. Recently, the smart contracts feature was added to the IOTA platform, which could enable the use of this DLT in many applications. It can be written in Rust and Solidity programming languages [39]. IOTA has the potential to be used in many sectors, for instance, P2P payments, supply chain, smart cities, smart grids, financial services, etc. There are other recent DLT platforms that are not based on blockchain structure, such as Hedera Hashgraph [40] and Holochain [41].

D. SMART CONTRACTS

The smart contract is a code stored in the blockchain in a decentralized way. The smart contract is a code that represents an agreement between different parties and is able to self-execute when specific terms or conditions are met. The main advantage of using blockchain to create smart contracts is that the contract is immutable and distributed. Therefore, once the contract is created, no one can delete or make

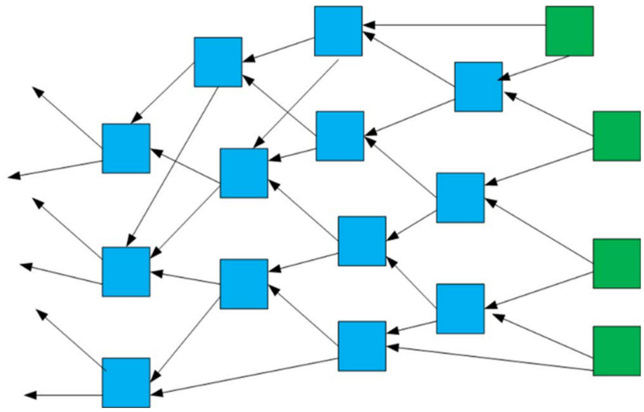

FIGURE 3. IOTA general structure.

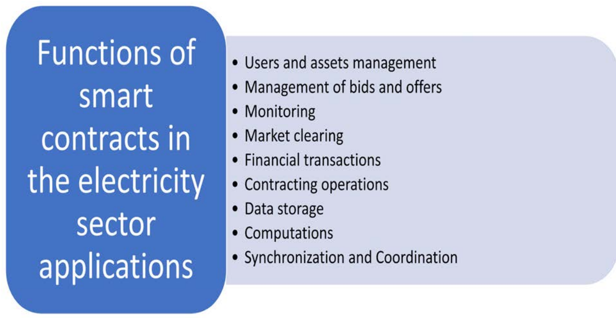

FIGURE 4. A list of functions of the smart contracts in the electricity sector applications.

changes to the contract. In addition, the contract is validated by all contract participants. The smart contract can automate many processes, and it is the reason to expand blockchain applications in many sectors other than cryptocurrencies. The smart contract is the key enabler of blockchain technology in electricity sector applications.

For different applications of blockchain technology in the electricity sector, smart contracts can provide different functions. A recent study [42] reviewed the functions of smart contracts in electricity sector applications. The smart contracts functions are described in detail in [42], and they are briefly described below. Fig. 4 lists the functions that smart contracts can provide.

1) USERS AND ASSETS MANAGEMENT

This function enables the registration and authentication of different assets (i.e., battery, load, etc.) [43] or users (i.e., consumer, prosumer, etc.) [44].

2) MANAGEMENT OF BIDS AND OFFERS

In this function, smart contracts implement a function to receive bids and offers from participants and save them. The bids and offers could contain different information such as energy amount, price, time of delivery, etc. [45], [46].

3) MONITORING

The smart contract is used to gather measurement data of registered devices such as smart meters and ensure the data

TABLE 3. Comparison between DLT platforms.

Features	Bitcoin	Ethereum	EWC	Hyperledger	IOTA
Governance	Bitcoin Developers	Ethereum Developers	EWF	Linux Foundation	IOTA Foundation
Platform Description	Payment	General purpose	Energy applications	General Purpose	General Purpose (IoT)
Cryptocurrency	Bitcoin	Ether	EWT	No, but it can be added if required	MIOTA
Consensus	PoW (SHA-256)	PoW (Ethash), PoS (soon)	PoAu	PBFT	FPC
Network	Public	Public	Private	Private, consortium	Public
Programming Language	C++	Python, Golang	Python, Golang	Java, Golang	Java, Javascript, Golang,Python, C#
Smart Contract	No	Yes (Solidity)	Yes (C, C++, and others)	Yes (Java, Golang)	Yes (Rust, Solidity)
Mining	Yes	Yes	No	No	No
Transactions Fees	Yes	Yes	Yes	No	No
Structure	Blockchain	Blockchain	Blockchain	Blockchain	Tangle
Scalability	No	No	No	No	Yes
Electricity Sector Projects	No	Power Ledger Grid+	Electron EW Origin	TenneT Energy Blockchain Labs	No

integrity by receiving it from a trusted asset. The data can be for energy production, energy consumption, the action of the device to a request from the system operator, etc. [47], [48].

4) MARKET CLEARING

Smart contracts can be used to match bids and offers by different market participants in a decentralized way without the need for a central entity. Many methods were developed to achieve this, such as auction mechanisms [49], [50].

5) FINANCIAL TRANSACTIONS

Smart contracts enable automatic transactions of value after specific conditions are met. For instance, after a prosumer delivers energy to a neighboring consumer, money will be transferred from the consumer wallet to the prosumer wallet [51]–[53].

6) CONTRACTING OPERATIONS

Smart contracts can be used to reach an agreement between entities or participants and to sign the contract automatically [54].

7) DATA STORAGE

Smart contracts can store contractual commitments data such as involved participants, the quantity of energy to be traded, price, and time of delivery. Additionally, it can store the data of real production, real consumption, or participant action [55], [56].

8) COMPUTATIONS

Smart contracts enable doing computations which is very important for applications in the electricity sector which enables smart contracts to take a control action depending on input data from devices connected to the grid [57], [58]. However, there is a limitation to performing complex computations because of the high cost of running them on the blockchain.

9) SYNCHRONIZATION AND COORDINATION

Smart contracts can be used to coordinate a large number of devices to achieve a common objective or provide an ancillary service without the need of a central entity (i.e., aggregator) [59], [60].

III. BLOCKCHAIN POTENTIAL APPLICATIONS IN THE ELECTRICITY SECTOR

Due to economic, technical, political, and environmental drivers, the electricity grid is moving to decarbonization, decentralization, democratization, and digitalization [61]. Decarbonization refers to electricity generation from RESs which are not based on fossil fuels. Decentralization refers to generation at a small scale at the distribution level and not only from large power plants and the ability to trade and consume the produced energy locally. Democratization refers to the transformation from power systems dominated, operated, and controlled by large companies to a power system with a significant role for small consumers, producers, and prosumers. Digitalization refers to the large adoption of information and communication technology (ICT), smart metering devices, smart devices, IoT, etc., especially at the distribution level.

This transition will lead to many challenges in managing and controlling the power grid due to the unpredictable and intermittent nature of RESs and the difficulty of managing and controlling millions of active consumers and small producers dispersed in wide geographical areas. Despite the benefits of digitalization, it may increase the power system's vulnerability to cyber-attacks. Also, the data collected by smart devices raises a privacy concern [61]. The present structure of the electric power system and electricity market is unsuitable for achieving this transition. In addition, up till now, the incentives for active consumers are insufficient, and small producers cannot participate in the electricity market. Therefore, there is a need for innovative technologies to achieve the smart grid transition and facilitate the management and operation of the grid while considering security and privacy issues. One of the promising technologies that may have a crucial role in smart grids is blockchain. Many researchers, utilities, companies, and electricity sector decision-makers believe that blockchain and its desired features can help the shift to the smart grid and achieve decarbonization, decentralization, democratization, and digitalization of electric power systems. Blockchain can also enhance transparency and data security, optimize processes, and decrease transaction costs.

Current electricity markets operate in a centralized manner, and the consumer can buy electricity from utilities only. In the future power system, a large percentage of electricity will be generated locally, and many consumers will become prosumers with generation capability. Consumers will have the choice to buy electricity from nearby prosumer or utilities. Therefore, there will be a need for a competitive local (i.e., P2P) electricity market that maximizes prosumers' and consumers' benefits. In previous years many research studies and projects investigated how blockchain can enhance different electricity markets like wholesale and retail markets and create a P2P market. Furthermore, they studied how it can be used in EV charging, RECs and carbon credits trading, enhancing power system cybersecurity, metering and billing, investment in RESs, and Power System Operation and Management.

Blockchain applications in the electricity sector are being investigated by both academic institutions and industry. Therefore, in each field of activity, examples of scholarly publications, industry projects, or startups are presented. The blockchain applications in the electricity sector were classified into eight domains according to the field of activity, as shown in Fig. 5. A large number of research studies, projects, and startups were presented to show the research and development activity in each area. In the following sections, the services that each startup can provide are discussed. The services that startups platforms are providing or can provide depend on the information provided by the startup's websites.

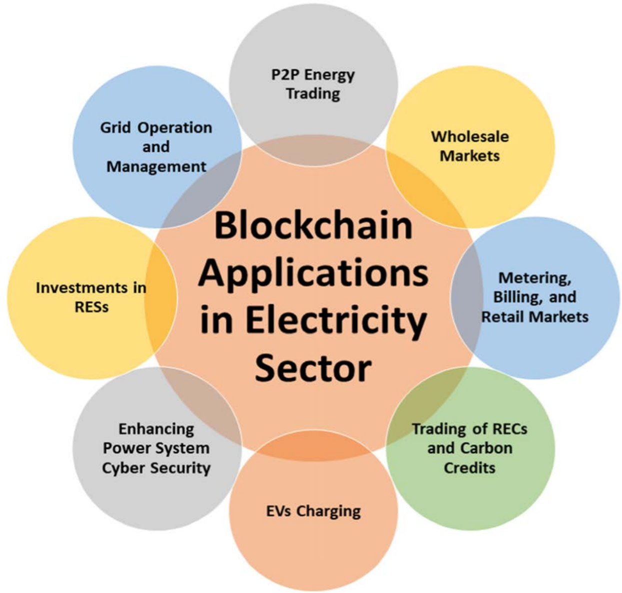

FIGURE 5. Classification of blockchain applications in the electricity sector.

A. PEER TO PEER ENERGY TRADING

There are an increasing number of small-scale distributed generation being installed. Currently, this generation can supply home, and the extra energy can be sold to the system at regulated prices or at wholesale prices. A new approach to enable local generation is by creating a local market in a community or microgrid where peers (i.e., consumers, prosumers, and producers) can buy and sell electric energy from each other (i.e., P2P energy trading) [62], [63] or energy can be traded between microgrids. In this case, the generated energy is consumed locally at acceptable prices for both prosumers and consumers, and the prices could reflect the availability of local renewable generation. Moreover, this could decrease the stress of the network and energy losses since part of electric energy demand is supplied locally and postpone grid upgrades and increase energy security [64]. However, to do this, all participants should have smart devices for monitoring and control, and communication infrastructure in order to buy and sell energy and provide ancillary services through the local electricity market. Furthermore, to what extent such markets become an exception of the current system, or they can be replicated largely, still is an open question.

Several studies and projects examined the applicability of the local electricity market and P2P energy trading using different technologies [65], [66]. Blockchain as a technology that naturally allows P2P interaction is proposed as a promising technology that can be used to implement local markets to match supply and demand offers, and exchange energy between neighbors in an automatic and efficient manner, and makes money transactions securely, rapidly, and cheaply. Blockchain can record the energy generation and consumption of all participants and the equivalent money each one should receive or pay and can make the transactions automatically (monthly, weekly, daily, or real-time) depending on design without intermediaries like banks or utility companies. It is very important to consider that traded electricity is delivered through the physical grid. Therefore, proper management and control of demand and supply should be provided to operate the grid within acceptable limits. As a result, the DSO will have a role as the owner and operator of the distribution grid at which the actual electricity trading is done. In order to use the grid for trading, a fee should be paid to DSO. Therefore, the electricity price in the P2P market should include this fee.

Most of the studies focusing on blockchain potential applications in the electricity sector are on P2P energy trading, which is considered the most promising application. Many studies investigated blockchain's application for creating a local electricity market (LEM) that enables participants to trade electricity P2P. In [67], a private blockchain-based LEM in a small community containing PV generation was developed, allowing prosumers and consumers to trade electricity without a third party. Ethereum platform smart contract and PoW consensus mechanism was used in this study to regulate electricity trading, record transactions, and execute payments. The main grid provides electricity to the community when community PV generation is insufficient to supply all consumers. In addition, the study conducted security analysis and proved system security against attacks. To overcome the weaknesses of blockchain technology such as scalability and need for miners, another study investigated the IOTA DLT platform for P2P energy trading [68]. The simulation results showed the feasibility of IOTA for creating platforms for P2P energy trading, and they recommended the real future implementation of the platform to confirm its feasibility.

Furthermore, using blockchain technology, microgrids can interact with each other in a P2P manner and exchange information and energy to provide services forming networked microgrids. This interaction can enable more efficient use of local resources than independent microgrids and lower electricity prices for consumers. In addition, it provides more flexibility at extreme events such as congestion or outage of the distribution network by adapting microgrids generation and demand to handle these events [69]. For instance, reference [70] proposed a blockchain-based mechanism for multi-directional P2P energy trading between microgrids. The mechanism was tested using the data of a real distribution network in Guizhou, China, with 14 microgrids. The results showed that the proposed mechanism increased RESs utilization and microgrids' profits.

In January 2019, a pilot project called Quertierstrom for creating a blockchain-based local P2P electricity market went live in a town in Switzerland called Walenstadt. The project aims to assess the local electricity markets' technical feasibility, user behavior, and market design. The project has 37 households participating. They used private blockchain Tendermint [71], and transactions are validated by energy producers. The participants can track their production and consumption and community production and consumption using a mobile application. In addition, they can set the price at which they are willing to buy or sell electricity. Based on a double auction mechanism, each participant's smart meter automatically submits a bid every 15 minutes and then the market is cleared.

The project continued for one year, and the results showed that with the blockchain-based local electricity market, the self-consumption in the community approximately doubled. Also, it was found that the participants usually opposed paying higher prices for locally produced energy than grid prices [72], [73]. The private blockchain used required small computational power and energy consumption. The small computers that were used as blockchain nodes and smart meters consumed about 4% of the traded electric energy. This value should decrease in order to clarify the added value of blockchain in terms of sustainability. The blockchain software proved its reliability, but they faced many failures in hardware. Moreover, they needed a smart meter with an application processor, which was not available in smart meters in the market. Therefore, they used self-developed modules on Raspberry Pi. Furthermore, the project faced scalability issues. They found that the system can handle up to 135 solar installations (i.e., transaction validators) and up to 600 consumers while remaining stable. The system can scale up by creating several blockchains in different neighborhoods [74].

In New York, USA, LO3 Energy company implemented the first demonstration project of the blockchain-based local market for P2P energy trading between prosumers and consumers in April 2016. In this project, known as Brooklyn microgrid, the prosumers can sell their excess PV generation to nearby consumers in the community. Prosumers can participate in the local market after installing smart meters, which monitor and record the energy data to be used in the local market, and they have the choice to sell the excess generation in the local market or to the grid by the feed-in tariff. Using the Brooklyn microgrid app, the consumers can select their electricity source to be locally PV generation, renewable generation from anywhere, or grid supply. Also, they can bid the price they are willing to pay for the local PV generation. Brooklyn microgrid provides the consumers control of the source of their energy. In addition, it gives more options to the prosumers and supports the community economy [75]. It should be mentioned that there are questions about scalability and infrastructure issues in this application. For instance, in Brooklyn microgrid, each participant in energy trading needed a computer to work as a blockchain node. LO3 collaborated on many other projects in the USA and other countries [76]. In 2018, Lo3 and eMotorWerks collaborated on a project to connect the Lo3 energy trading platform and eMotorWerks EV charging platform to enable the trading of locally generated renewable energy and EVs.

Lo3 platform is responsible for P2P transactions and price signals, whereas the eMotorWerks platform is responsible for matching local generation and demand (i.e., households and EVs) and controlling energy flow [77]. Brooklyn microgrid project was followed by many projects and startups that use blockchain for P2P energy trading.

An Australian startup Power Ledger developed a blockchain-based platform that enables many applications and services in the electricity sector. The main application of the platform is P2P energy trading. The platform enables the trading of locally generated (PV, wind, etc.) or stored (batteries or electric vehicles) electric energy between neighbors in a trustless environment and receiving money in real-time. In their first trial in Australia, they proved large potential revenues for electricity producers by selling their electricity at higher prices than the feed-in tariff in addition to reducing consumer bills by buying electricity at lower prices than utility charges. Power Ledger partnered many other projects outside Australia. In collaboration with Vector Energy, they developed a P2P energy trading platform for the distribution system in Auckland, New Zealand. Also, Power Ledger has projects in the USA, Japan, India, and Thailand. Power Ledger uses a hybrid public and consortium Ethereum blockchain [78].

A co-founder of EWF Grid Singularity developed an open-source blockchain platform for P2P energy exchange in a local community. This P2P local community market can reduce the community electricity bill, increase self-sufficiency, and reduce distribution grid congestion [79]. Prosume blockchain-based platform enables P2P energy exchange between neighbors with the participation of existing supplier or aggregator. The neighbors can trade their generation or storage and make revenues [80]. Another company in Slovenia called SunContract developed a P2P market platform using blockchain. The platform maximizes the consumer benefit by connecting producers and consumers in an open marketplace without intermediaries. The platform allows small local producers to sell their excess generation by bidding in the market and increasing their profit. Consumers can choose their energy source: wind, solar, hydro, or other sources, and they can select from different prices in addition to the ability to track daily electricity consumption [81]. In the Netherlands, Spectral company partnered with Dutch DSO Alliander to develop a local electricity market platform based on blockchain. The platform is called Jouliette, and it has a token to facilitate local trading of energy and P2P transactions between participants' wallets. In addition to P2P energy trading, the platform has other features such as production and consumption forecasting system based on machine learning, and community power flow in real-time [82]. In the Netherlands, a blockchain-based platform that allows P2P energy trading was developed by ToBlockChain company. The platform is called PowerToShare, and it was practically tested in the green village at TU Delft [83]. There are many other startups that developed or are developing projects for blockchain-based P2P energy trading.

Blockchain technology or DLT can be suitable for this use case because it provides many benefits that are significant for this application, such as decentralization, transparency, trust between market participants, enhance the role of end-users, preserve participants' identity and data privacy, security against cyber-attacks and malicious behavior, low transaction cost, and low operation cost by automating processes and reducing intermediaries. However, the adoption of the P2P energy trading (i.e., LEM) concept and blockchain-based P2P energy trading will take time until we can see it applied in power systems on a large scale because regulations defining this type of market are still missing. Furthermore, for practical implementation of LEM, there is a need for special hardware (i.e., smart metering) with advanced features than the currently installed smart meters in addition to distributed ICT, which require high investment and maintenance costs. Moreover, there is a need for more study of scalability issues even with using private blockchains in this use case. Also, the grid constraints limit the possibility of free trading of energy between prosumers and consumers. Additionally, the technology must prove its benefits for this use case outweigh the implementation cost. As a result of these barriers, blockchain-based P2P energy trading is still on the pilot scale and did not move to large-scale implementations.

B. WHOLESALE MARKETS

The current wholesale electricity markets have many intermediaries like regulators, banks, brokers, logistic providers, price reporters, and trading agents due to market complicated processes. Also, the wholesale market uses inefficient IT and communication systems in addition to many slow and time-consuming manual processes [84]. This result in high operation cost and high transaction cost. Currently, small-scale DERs have barriers to participate in the wholesale market in practice. Even if they are allowed to participate, in some cases, they cannot afford the current operation and transaction costs of wholesale markets. This structure of the wholesale market may not be suitable for future power systems containing a large number of DERs. Therefore, there is a need for innovative technologies to improve the wholesale market and make it suitable for the participation of DERs.

Blockchain was proposed as a technology that can enhance wholesale markets and decline their costs by connecting all participating parties without any intermediaries or with fewer intermediaries, and making more efficient operational processes with high transparency and autonomous trading actions [85] and providing more security of data and communication. Via blockchain, generation units can directly trade with retailers or consumers through autonomous trading agents. The trading agent finds out the best deal for the consumer at a specified time period. The agreement is registered in the blockchain and executed automatically at delivery time. Then payments are completed according to the agreement, and all transactions can be viewed by the system operator and all participants. The access of small consumers to the electricity markets opens the door for new flexibility services they can provide to the grid.

A limited number of research articles studied the application of blockchain technology on wholesale markets compared to P2P energy trading. For instance, the authors of [86] developed a blockchain-based wholesale market considering the Australian wholesale market as a case study. They aim to increase the security of the wholesale market trading system and improve the visibility of energy transactional data for end consumers so they can track the source of electric energy delivered to them. Additionally, the auditing of sales and payments is automated. Another study [87] developed a blockchain-based solution to enhance the efficiency of the accounting process of the current balancing markets. The proposed solution reduced the delay in the publication of the imbalance prices. Moreover, it resulted in fast and auditable financial transactions.

Ponton is a German company that has been working on the creation of P2P integration platforms in the energy sector for many years. They were using messaging services for exchanging data. Currently, they are using blockchain as well for P2P integration projects. Ponton has a blockchain-based project called ''Enerchain'' that looks up to decline wholesale energy trading related costs by enabling P2P trading between wholesale market participants for electricity or gas. They started development in 2016 with the collaboration of more than 40 companies and utilities and executed many short tests to enhance platform performance and security against cyber-attacks and they went live in May 2019. They used tendermint platform with permissioned blockchain, which enabled 200ms consensus time and only 1s for block creation, which is a very fast block time compared to other platforms like Ethereum. Enerchain is suitable to be used for local trading of energy in small communities as well. Ponton also is a partner in the German project NEW 4.0. In this project, Ponton is developing a blockchain-based platform to trade flexibility between many market participants, which are companies and utilities in this case. The participants change their production or consumption based on the prices in the market [88].

Although blockchain has the potential to change the wholesale market structure, there are a few challenges to tackle. This application requires changes in regulations due to the variations in the roles of intermediaries such as trading agents and brokers [89]. Moreover, the number of transactions that blockchain-based on PoW consensus can handle is very small compared to current electronic payment systems, which represents a technical challenge. Other consensus mechanisms like PoS and PoAu can be a solution to this issue, but they are immature yet compared to PoW. Furthermore, open access to important commercial information about the market is a crucial issue. In addition, it is very challenging to implement large changes in market structure in a short time period. Therefore, most of the blockchain projects in this area focus on one part of the electricity market. Blockchain application in imbalances settlement received huge attention. The imbalances settlement takes long durations and may take many months [61]. The use of blockchain can reduce these delays and accompanying costs by decreasing back-office operations. It can trace and record electricity generation and consumption and accelerate payments.

C. METERING, BILLING, AND RETAIL MARKETS

There are many inefficiencies in the current metering and billing of electricity usage in many countries due to the manual processes involved, which result in high administrative costs. Moreover, it has very low transparency and privacy-preserving levels. The application of blockchain in any use case can provide processes automation, high transparency, privacy-preserving, security, etc. Therefore, the application of blockchain technology in metering and billing is being studied by many research initiatives to assess its suitability to tackle the previous challenges. Blockchain technology integrated with smart metering infrastructure has the potential to reduce administrative costs by automating billing processes for consumers, prosumers, and producers while securing customer identity and data. Blockchain enables traceability of the origin of energy produced or consumed at any point and the cost of energy which leads to transparent energy charges.

Few studies investigated blockchain-based metering and billing. For instance, reference [90] implemented a prototype for blockchain and IoT-based metering and billing of small consumers at the distribution network. Hyper ledger fabric blockchain was used due to its scalability and low energy requirements features. The IoT devices were used as smart meters to measure and record energy consumption on the blockchain. The proposed system is less vulnerable to cyber attacks due to data encryption and its decentralized architecture. Consumers have full control over their encrypted data, and they share it when necessary. Many processes could be automated using smart contracts. Another study implemented a prototype for a decentralized and secure recording of power consumption of residential consumers using blockchain and IoT [91]. The study used the Ethereum blockchain platform for implementation. This proposal aims to test the feasibility of blockchain and IoT in this use case. In addition, it aims to tackle security and single point of failure in centralized architecture for energy consumption tracking and recording and increase automation.

Many companies accepted cryptocurrencies for energy and electricity bills payment. Bankeymoon, a South African startup that offers blockchain-based services and solutions, developed a platform for the prepayment of electricity using cryptocurrencies. This allows prepayment easily without the need to be physically nearby [92], [93].

A Spanish startup called Pylon developed a blockchain-based neutral database to store the users' consumption and production data. Pylon gives the users control over their data and to whom they want to share it (i.e., energy service provider or retailer). Then the retailer can provide digital services that can help users reduce their energy bills. Also, high-quality user data can help retailers provide tailored personalized services based on user requirements [94]. Prosume developed a blockchain-based platform that offers various applications in the electricity sector [80]. Prosume platform enables the user to monitor the energy consumption or production of each device and energy expenses, helping him to manage the consumption to reduce energy bills. By using smart contracts, it also offers automatic payments, which reduce billing administrative costs for energy providers and minimize payment delays. The payments are executed every 15 minutes between energy wallets [80]. Also, other companies are investigating the use of blockchain for water and gas metering systems [12]. Although the transaction cost of platforms like Bitcoin and Ethereum is not low, which makes microtransactions (i.e., hourly or daily payments) uneconomical. There are ways to reduce these costs, such as payment channels and other platforms which promise zero fees transactions, such as IOTA.

Blockchain can improve the retail market by enabling real-time trading settlement. This can reduce payment processing costs. It provides customers more transparency of their consumption, electricity charges, bill components, and electric energy sources (i.e., renewable or non-renewable). Blockchain can optimize and automate retail processes, metering and billing systems, and reduce administrative costs. It can also facilitate the access of small consumers and producers to wholesale electricity markets, which increases competitiveness and reduce the end consumer electricity bill. Blockchain can also facilitate the switching between retailers for small consumers. For instance, reference [95] implemented a proof of concept of a blockchain-based system for switching between retailers. The proposed system aims to facilitate the process of switching between retailers by automating all the processes by eliminating inefficiencies in the currently used process, such as lack of direct communication between stakeholders, lack of automation, and non-existence of common data management system. The proposed system can reduce the time for switching between retailers from a month to less than a day. This can reduce the barriers for new retailers to enter the market, which results in increased competitiveness.

Few startups used blockchain to improve retail markets. Restart Energy is a Romanian private energy and gas supplier that developed a blockchain-based platform for decentralized energy trading and many other services. The platform enables consumers to buy energy directly from producers, which reduces 30% of consumers' electricity bills, and producers will sell energy 30% higher than the wholesale price. Also, it allows anyone to operate as a retailer in a small area or city, in any deregulated market, and make profits using the platform, a service they call energy franchise. Using their Tokens, they claimed that their platform enables trading energy worldwide [96].

Grid+ startup operated by ConsenSys is using AI and Ethereum blockchain to operate as an electricity retailer that connects consumers directly to the wholesale market and allows consumers to buy and sell electricity at the best prices. Grid+ aims to reduce the end consumer electricity bill by reducing the administrative cost the current retailers charge and by giving consumers access to wholesale market prices and buying electricity at the lowest prices. Grid+ developed a device (i.e., hardware and software) that can track consumer daily electricity consumption patterns and predict future demand and buy electricity at the lowest possible price at the day-ahead market on behalf of the user. Also, Grid+ enables prosumers with a small generation to sell their energy at market prices. It allows consumers who own batteries can buy electricity when the price is low and sell it back when the price is high. It provides transparent pricing and fast billing and payment every 15 minutes by blockchain [97].

It should be considered that integrating blockchain with smart metering infrastructure requires a high investment cost because the smart meters being deployed now in many countries do not support blockchain requirements. Also, managing smart meters data using a public blockchain could raise a privacy concern because the consumption and production data and executed transactions can be accessed by all parties (i.e., nodes). Therefore, developing methods to anonymize users' information and make it untraceable is very important. Another challenge is the management and storage of large data in distributed ledgers and the accompanying high costs [12].

D. TRADING OF RENEWABLE ENERGY CERTIFICATES AND CARBON CREDITS

There are worldwide concerns about greenhouse gases (GHGs) emissions. One of the effective methods of emission reduction is to enforce a price on emissions to reduce the resistance to decrease emission production. Tradable permits (also known as emission trading schemes (ETSs), emission certificates, and carbon credits) are the most commonly used method to levy a price for emissions. The governments issue permits which specify a limit or a cap of emissions the entity can produce. The permits can be traded between entities. Entities with more emissions than their permits can buy permits from entities with less emissions than their permits. Many countries activated ETSs (i.e., carbon markets), and other governments are studying its implementation. However, the current ETSs are complex, fragmented, and still have some limitations that affect their effectiveness, such as manual auditing by authorities, which increases errors and fraud possibilities.

Transparency, security, tamper-proof, and immutability features of blockchain can increase ETSs transparency and reduce fraud. Blockchain transparency enables easy access to emission information and proofing while keeping a certain privacy level. Security, tamper-proof, and immutability features protect the system from double counting issues and fraud. Moreover, its ability to simplify and automate many processes in the issuance and trading of permits in addition to fast and low-cost transactions, makes it a suitable technology for ETSs. Few studies examined the application of blockchain in ETSs. In [98], the authors proposed a blockchain-based ETS, which is suitable for future applications that have a high degree of automation and digitization. Also, they used a reputation-based system that manifests the participant effort in adopting long-term solutions for reducing emissions. Participants with a good reputation can get access to better offers and finish the trading process faster than participants with less reputation. The use of blockchain could eliminate the need for a central organization to manage bids and offers of participants. The proposed ETS can enhance traditional ETSs efficiency and tackle management and fraud issues. Moreover, it incentivizes participants to adopt long-term solutions for reducing emissions. In [99], the application of blockchain technology in existing carbon markets was investigated, with a focus on the Australian carbon market as a case study. The study concluded that the proposed method could improve the carbon market performance and efficiency, reduce transaction costs, and increase transparency and equity.

Generating high shares of electricity from RESs is very crucial to achieve sustainability and reduce GHGs emissions. However, some RESs technologies under certain market conditions still have a higher cost per MWh than wholesale market prices, which makes them non-cost competitive. Therefore, governments use incentives like subsidies to incentivize investments in renewable energy generation. Another method to motivate investments in RESs and increase revenues for investors is green certificates or renewable energy certificates (RECs). When an electricity producer generates a specific amount of electricity (i.e., 1 MWh) from renewable generators, he receives a REC from the government as proof that this amount of energy is generated from renewable generation. The REC contains information about who generated this renewable energy, when, where, and how. The producer can sell the certificate in the RECs market and gain revenues additional to selling electrical energy. RECs are bought by entities that want to decrease their carbon footprints, entities and people that want to support electricity generation from RESs, or in some countries these become a mandatory purchase for retailers to have a certain amount of energy from RESs.

A big issue of traditional RECs markets is that it is not accessible by everyone due to regulatory barriers and high costs. Therefore, ordinary consumers and small producers cannot participate in it and buy or sell the RECS directly without intermediaries. Blockchain's ability to create an open RECs market where renewable energy producers and consumers interact directly is investigated in a few studies. For example, in [100], a RECs market was simulated using the Ethereum platform. The proposed market allows direct transactions between producers and consumers. Smart contracts define the trading rules and execute trading, working as marketplace and market operator. The results showed that blockchain could be used to create a robust platform for RECs trading with low operating costs.

Many developers are using blockchain to automate the issuance of carbon credits and RECs and facilitate their trading and payments. Autonomous organization developed an open-source blockchain-based public platform for climate initiatives called DAO IPCI. The platform integrates many climate-related functions such as carbon credits, environmental credits, environmental assets, renewable energy credits, and others. The platform uses blockchain to enable possible international interactions between carbon markets, reliable and transparent transactions, and better coordination between stakeholders [101]. In collaboration with IBM, Energy Blockchain Labs in China developed a blockchain-based platform that enables entities to monitor and quantify their carbon emissions and buy carbon credits from entities with low emissions to compensate for their excess emissions. The platform easily links all stakeholders such as governments, companies, regulators, etc. Energy Blockchain Labs believe that blockchain can enhance the efficiency of carbon credits trading and streamline its processes [102].

Power Ledger platform integrated with smart meters can monitor and track the energy generation from RESs and create RECs, and it can track the energy usage of any industrial facility and specify how much carbon credits should be bought [103]. Also, it offers a transparent and efficient digital market for trading RECs and carbon credits, where buyers and sellers can interact directly in this market with no intermediaries and low transaction costs. Therefore, using blockchain, the whole process can be automated from creating credits, trading in the market, credit transfer to the buyer, and transactions. EW origin is a decentralized opensource application that records the energy generated from RESs at the kWh level and automatically issues RECs, which enables the participation of small producers that were previously excluded. It records and tracks the energy source, location, and time of production. Also, it offers a market for buying and selling emission credits or any green attributes. It results in lower costs for origin tracking, certificates issuance, certificates trading, and easy access to the transparent market for buyers and producers of different sizes [104]. Another company SPgroup developed a blockchain-based application for trading RECs worldwide. It allows the trading of RECs for a small amount of generated energy (i.e., 1 kWh) [105]. Both EW origin and SPgroup are running on EWC.

Poseidon is working on neutralizing the footprint of our daily life activities and purchases by supporting projects that decrease GHG emissions, such as forests. These projects are supported by buying their carbon credits. Poseidon carbon credit is equivalent to 1 metric ton of CO2 emissions being avoided. Poseidon used blockchain in its platform to enable transparency, fast microtransactions, and traceability of donations which are publicly available and permanently stored [106]. CarbonX is using blockchain to fight climate change. CarbonX developed a blockchain-based platform that enables companies to compensate for their carbon emissions easily and efficiently and motivate customers to buy their carbon-neutral services or products. CarbonX buys carbon offsets such as forests or methane capture and issues them as zero footprint (ZFP) tokens on a private blockchain, and these

ZFP tokens can be purchased by companies to compensate for their carbon emissions. Blockchain provides transparency and security of transactions and enables company stakeholders to verify carbon offsets' origin [107].

From previous academic studies and industrial efforts, it can be seen the promising potential of blockchain technology in this use case. Blockchain can track the energy generation from RESs and energy usage of industrial facilities and specify how much carbon credits should be bought. It can automate the issuance of RECs and carbon credits, operate as a digital trading platform to match the buyers' and sellers' bids, transfer the certificate or credit to the buyer, and execute financial transactions from buyer to seller. The blockchain-based carbon market or RECs market allows P2P interactions between all stakeholders, such as energy producers, governments, companies, regulators, etc., with no need for central intermediaries to manage the market. It can enable the creation of an international market for trading environment credits. Automating the processes and reducing operation costs enables the issuance of RECs at the 1kWh level and allows small producers to trade RECs. Additionally, blockchain enhances market transparency, reduces cost by automating processes and low-cost transactions, preserves the privacy of participants' identity and data, and improves security against tampering and fraud.

E. ELECTRIC VEHICLES CHARGING

EVs number is increasing continuously and crossed 5 million in 2018 and is expected to be between 130 and 250 million in 2030 [108]. EVs can be charged by private home chargers, street chargers, and fast-charging stations [109]. Also, a potential way of charging is vehicle to vehicle (V2V), where an EV with surplus energy discharges part of the stored energy to another EV with an energy deficit. One of the major barriers to EVs adoption is the lack of public charging infrastructure. A recent IEA report showed that most of the installed EV chargers are private chargers that are used only by one person [108]. There is a need to develop methods to enable access to private EV chargers for other EV owners while preserving security and privacy for EV owners and EV charger owners. Blockchain can enable EV owners to share their private home chargers with others in a P2P manner to gain profit without intermediaries (i.e., banks or financial institutions).

Several studies presented how Blockchain can be used for payment (i.e., transactions) for charging EVs [110]–[112]. The authors of [113] used blockchain for secure EVs charging in smart communities while maximizing operator utilities and satisfying EV owners' preferences. In [114], the authors discussed how smart contracts can be used to make EVs automatically choose the best charging station in real-time based on the charging price they bid. In [115], the authors discussed a similar application of blockchain to select the suitable charging station based on the price they bid and the distance to charging stations while keeping EV owner privacy. Other developments can be made on the platform so that the charging station selection can consider many other parameters such as waiting time, charging time, EV owner preferences, etc. In [116], they implemented a decentralized P2P energy trading between EVs (i.e., V2V) to satisfy the electricity demand of nearby EVs locally. A consortium blockchain was used for making secure and privacy-preserving transactions, and it was proved by security analysis. In this study, local aggregators are responsible for maintaining blockchain network and managing an auction mechanism between EVs willing to buy or sell electricity. The authors of [117] used blockchain to solve the trust issue between EV owner and battery swapping charging stations. Blockchain was used to store all the battery data and to make transactions. In [118], they used blockchain and IoT to implement battery swapping management system.

Many companies explored the applications of blockchain on EVs. Share&Charge was the first to develop a blockchain-based platform for EVs applications. It started in Germany in 2017 with the objective of fostering EVs adoption. It enables EV owners to get access to private EV chargers and public charging stations in a P2P manner. Using the Share&Charge app, people can share their private EV chargers when they are not using them and get revenues. It is similar to renting your unused room on Airbnb. The charger owners can set their prices which can be visualized by the EV owner in real-time to choose the appropriate one and pay with Share&Charge easily [119]. First, it was running on the public Ethereum network. Due to the technical and economic issues like high and volatile fees, they switched to consortium blockchain [120], where both EWC and Ethereum are used [121]. Later, all the processes are done off-chain, and only the final settlement transaction is done on the blockchain network. Share&Charge is still in phase1, and many other features such as smart charging and smart grid integration will be available in future developments [121].

Share&Charge collaborated with other companies in projects for applications of blockchain on EVs. For instance, Share&Charge and eMotorWerks started a pilot project in 2017 in California that uses eMotorWerks smart charging technology and Share&Charge blockchain-based platform to enable P2P sharing of charging infrastructure (i.e., private and public chargers). The project aims to increase the availability of EV charging infrastructure by making EV owners share their private Chargers [122], [123]. Another partnership between Share&Charge and Oxygen Initiative, a company in California to use Share&Charge platform for EV charging payment. Moreover, Power Ledger is developing applications for EV charging on their platform, which allows metering in real-time and fast transactions [78]. These blockchain-based projects can also motivate people to build EV charging stations even if they do not have EVs as a kind of business to gain profit which will increase EV charging infrastructure. A European TSO TenneT started a pilot project in 2017 partnered with Vandebron company for the application of permissioned blockchain based on Hyperledger Fabric for grid management in the Netherlands. In this project, Vandebron made EV batteries capacity available to be used by TenneT for grid balancing by controlling their charging and discharging. Blockchain was used to record the availability of each EV and its response to the TenneT signal [124].

Blockchain-based EVs charging can enhance system security from cyber attacks or malicious behavior from participants (i.e., aggregator, EV owner, etc.) due to its tamperproof feature and reserve EVs data privacy from data leakage by data encryption and provide trust without the need of a trusted intermediary. Moreover, it can automate many processes using smart contracts. The discussed research studies, startups, and pilot projects in this section showed that blockchain can enable secure financial transactions between different stakeholders and can help the management of EVs charging and discharging to provide grid services.

It is clear that blockchain has many potential applications for EVs. However, there are a few challenges that have to be considered while studying the blockchain applications for EVs. If a public blockchain is used in the application, the EV owners' data must be completely anonymous to protect their privacy and information about daily movements. Also, in order to ensure EV safety, the blockchain network has to be tamper-proof. Moreover, the transactions fees should be lower than other payment methods and with low latency. This requirement is violated in public blockchain networks like Bitcoin and Ethereum due to the high transaction fees and latency, but it may be solved by future developments in blockchain technology or by other DLTs. Additionally, the use of public blockchain for EVs can be infeasible if EVs will participate as a full node which requires high computational power. Therefore, many studies proposed the use of consortium blockchain where local aggregators are responsible for auditing and validating transactions or to use private blockchain where selected EVs are responsible for auditing and validating transactions. Furthermore, scheduling of EVs charging using complex algorithms run on a blockchain can be expensive due to the high transaction fees (e.g., Ethereum gas fees). Therefore, the algorithm can run off-chain to avoid this high cost [125]. As EVs can interact with the power grid, interoperability between EVs and power systems is important to provide benefits to both of them. Despite this recent progress from a few startups and system operators, large-scale integration of blockchain technology with EV infrastructure is still missing.

F. ENHANCING POWER SYSTEM CYBER SECURITY

The cybersecurity of the power system is crucial for normal, reliable, and safe grid operation. It refers to securing computer systems and communication channels of the power system. The power system was subjected to cyber-attacks in the past [126] and is expected to increase in the future with grid digitalization. The attackers use several methods, such as data injection attacks or denial of service in order to gain control of the grid. The attackers may manipulate grid data at the measurement node (i.e., meter or sensor) or during data transmission or gain control of the power system. The cyber-attack can occur at any location of the grid (consumer, distribution, transmission, and generation). These attacks may result in power outages in some regions, complete grid blackouts, and damage to power system components [127].

With the increase of DERs, the distribution system becomes more complex. System operators face the challenge of collecting, storing, protecting, and analyzing huge amounts of data for the current state of the power system. Traditionally, the data is stored in reliable central databases. However, the centralized storage of data is subjected to security issues such as malicious tampering and a single point of failure. In addition, already in some European countries smart meters are installed in almost all houses, measuring house consumption in real-time. Getting access to or stealing this data by malicious bodies during transmission to control centers reveals the house owner's electricity usage pattern. Therefore, there is a need for decentralized, secure, and reliable storage and communication methods. Blockchain is proposed as a good option to face these challenges due to its immutability and security features [128]. Blockchain in addition to cryptographic algorithms can ensure data privacy, cyber-attacks resiliency, and identity management.

Few studies investigated how blockchain can enhance power system cybersecurity. In [129], two possible scenarios of cyber-attacks were presented. In the first scenario, the attack occurs at the synchronous generator and gains control of the generator controllers or the connected load switch. The attack may result in losing the synchronism of the generator with the grid or even damage to the generator. The blockchain can be used to monitor the system in real-time to detect any malicious or abnormal behavior and to take actions that eliminate any possible damages. In the second scenario, a denial of service attack occurs in the distribution system, which makes the channels for data communication not working. This will affect monitoring and controlling units, and in case of any disturbances occurrence, a corrective control action cannot be made and may result in a power outage eventually. Blockchain DApps can be used to connect all stakeholders at the distribution system (i.e., utility. Consumer, prosumer, etc.). Also, distribution system status data (i.e., voltage, current, power consumption, etc.) is continuously stored in the blockchain. The blockchain data and data collected by communication channels will be compared, which enables blockchain to provide data on the distribution system status even if there is a cyber-attack. In the mentioned scenarios, blockchain will work as a secondary control that can minimize the power outages or losses caused by the cyber-attack.

In [130], a lightweight algorithm and blockchain were used to detect any tampering with smart meters data or malicious behavior and hence increase data security. Data aggregation is an effective method to protect end-users data during transmission to control centers. Data aggregation refers to aggregating the consumption or production data of end-users located in a geographical area. This aggregated data helps the system operator to be aware of the grid status and take decisions accordingly. The current structure of meter data aggregation is centralized in energy management systems. This structure has the risk of a single point of failure and privacy protection. In [131], a privacy-preserving, secure, and distributed data aggregation method for aggregating smart meters data was proposed. The method used homomorphic encryption and blockchain. Homomorphic encryption is used for smart meters data encryption, while blockchain is used for data aggregation and storage in a distributed way on all system nodes. The proposed method proved its ability to protect the privacy and resist data tampering. Another study [132] proposed a consortium blockchain-based data aggregation and regulation mechanism for smart grid. The security analysis showed that the proposed mechanism met the security requirement and has advantages in terms of communication and computation costs.

G. INVESTMENT IN RENEWABLE ENERGY SOURCES

Many people are interested in investing in RESs such as PV or wind. However, there are many barriers, for instance, unsuitable house roof, small house yard, living in an apartment building, high initial cost, etc. Therefore, not everyone can invest in renewable generation. A proposed idea is the co-ownership of renewable energy assets or energy storage by paying a share of the initial investment and getting a percentage of the revenues from selling the generated energy depending on your investment. Blockchain can be used for initial investment and automating the revenues division between all investors. This method can be used for small renewable generation or even large-scale renewable generation, which can increase the democratization of ownership in future power systems assets. Moreover, many startups are using blockchain-based tokens to raise funding and attract investment which is known as Initial Coin Offering (ICO).

A limited number of studies proposed the DLT-based shared ownership of assets in the electricity sector. Ref. [133] proposed the idea of DLT-based crowed funding for RESs projects taking offshore wind farms as an example. The results showed the cost-effectiveness of crowdfunding using DLT over bank loans for investments in offshore wind farms in New Jersey, USA. Another study [134] proposed an IOTA-based crowdfunding platform for residential PV projects, taking advantage of the new digital financial innovations such as DLTs. The proposed approach is an alternative to the traditional approach of funding from banks. The results showed that DLT-based crowdfunding could reduce levelized cost of electricity (LCOE) and financial costs of PV projects in many European countries compared to traditional investment options. The same concept of DLT-based crowdfunding could be used for financing other grid assets. For instance, in [135], they proposed a blockchain-based approach for crowdfunding of residential-scale batteries.

Sun Exchange company uses blockchain to facilitate the co-funding of PV projects. Anyone in the world can buy a share in a new PV project and receive revenues from the clean electricity generated for the next 20 years. The investors' revenues are paid in Bitcoin, which facilitates international transactions. Sun Exchange projects are focused on developing countries that face a lack of electricity access and with high solar irradiation and have difficulties to get funding from traditional financial institutions such as banks. Sun Exchange installed more than 15 PV systems in South Africa for schools, factories, parks, commercial businesses, etc. and there are projects under installation and others are collecting funds. They funded PV projects with capacities ranging from 15 kWp to 203 kWp [136]. Prosume introduced a feature in its platform which allows people in a community to co-own a community energy storage or generation [137]. ImpactPPA developed a blockchain-based platform to fund renewable energy generation projects in places that lacks access to electricity and to manage payment of electricity consumed. ImpactPPA has two types of tokens MPAQ token and GEN token. MPAQ token are bought by investors, and it represents the share of investors in the project, and it is used to fund the project and account revenues for each investor. GEN token is used by consumers to pay for electricity used [138].

WePower is using blockchain and smart contracts to allow everybody to invest in green energy and foster its growth. WePower exchange platform connects investors and companies willing to trade and invest in green energy and renewable energy producers. With a power purchase agreement (PPA), which is a contract between producers and companies, companies are able to purchase green energy at a fixed price for a specific duration. The traditional PPA process is complex and requires high transaction fees. That's why blockchain-based digital PPA is used in the platform, which simplifies processes and reduces costs making it accessible to a larger number of consumers, even small consumers. In the platform, green energy producers can sell future energy production in advance in an auction specifying the price and energy to be produced, and they provide information about the project as well. Also, consumers can make bids for the amount of energy they need at the price they are willing to pay [139].

Few companies are using blockchain for developing methods to incentive renewable energy producers. A blockchain-based startup called SolarCoin is using cryptocurrencies to motivate investment in solar production by giving a reward on solar generation as extra revenue for selling electricity production. The producer receives one solar coin for each 1 MWh of solar generation [140]. Local-e allows people in a community to support producers of renewable energy. The supporter pays a specific charge for every 100-kWh generated from renewable sources. This could motivate more people to install renewable energy generators [141].

H. GRID OPERATION AND MANAGEMENT

A large number of DERs are being installed. DERs make grid operation and management more complex and challenging. Also, flexibility is very important for any power system, especially with high penetration of uncertain, intermittent, and unpredictable RESs. System operators aim to enhance flexibility in future power systems; and need innovative technologies and methods to operate the future power system in a reliable and efficient manner. It is expected that blockchain can provide solutions for decentralized management and automation of the grid, improving supply and demand balance, and improving coordination between TSO, DSO, aggregators, balance responsible parties (BRP), and other participants in grid operation.

Many references studied blockchain applications in improving power system operation and management. For example, in [142], the blockchain was used to create a local electricity market managed by an aggregator operating as a VPP. In this market, small prosumers and consumers were allowed to sell and buy electricity and provide services to the power system. The prosumers and consumers send their energy and power flexibility bids to the aggregator. Then, based on the aggregated bids of the prosumers and consumers, the aggregator makes offers in the day ahead and ancillary services markets. When the aggregator delivers a service that is asked by TSO, the aggregator and participating prosumers and consumers get a reward. In contrast, if they fail to deliver the service they offer, they will be penalized. Blockchain is responsible for storing the production and consumption data of all participants and executing financial transactions.

The authors of [143] presented a blockchain-based decentralized energy management system for a community containing local RESs and smart buildings. The blockchain is responsible for monitoring production and consumption in the community, communication between community participants, and billing. The proposed management system enables coordination between community participants to achieve a common objective such as reducing community electricity cost, providing grid service, or maximizing local consumption of community RESs production without the need for a central entity like an aggregator. Each participant manages his production or consumption in order to achieve the community's common objective. The results showed that the proposed management system could flatten the community load profile and reduce consumption at expensive peak hours. In addition, approximately all the local RESs generation are consumed locally.

Many studies investigated the use of blockchain to manage economic transactions in the energy community or microgrid, and usually, they do not consider grid technical constraints. This study [144] used blockchain for the economic and technical management of a microgrid. The study considered the microgrid operation in grid-connected and islanded mode. The DSO manages active power trading between producers and consumers while considering microgrid technical constraints. Moreover, optimal power flow was used to find the optimal set points of reactive power injection that can reduce the power losses, improve voltage profile, and respect grid constraints. The generators provide voltage regulation by reactive power injection and receive a reward. The blockchain tracks the active power trading and reactive power injection and executes the corresponding financial transactions.

Many startups, utilities, and system operators are investigating blockchain capabilities in improving power system operation and management. Prosume blockchain platform enables easy interaction between TSO, DSO, and aggregators which are connected to prosumers and consumers. Through these efficient interactions, consumers and prosumers can respond to requests from TSO or DSO to change their production or consumption to provide grid services [80]. Ponton developed a pilot software based on blockchain called GridChain. The software was developed after a number of Austrian DSOs asked Ponton company to explore the abilities of blockchain in the integration of grid processes. The software simulates future grid management processes in real-time and will be tested practically in the field soon. The software could coordinate the balancing requests between TSOs, generation units, aggregators, and DSOs in seconds and facilitate congestion management. The settlement time was significantly reduced to 15 minutes [145]. Power Ledger platform enables prosumers with DERs to provide flexibility services such as congestion management to power system operators and get paid by them. Infrastructure upgrades could be deferred by capturing flexibility from these DERs [146].

A European TSO TenneT started two pilot projects in 2017 for the application of permissioned blockchain (i.e., Hyperledger Fabric) in grid management in Germany and the Netherlands [124]. The first pilot project was in Germany in collaboration with Sonnen company. In this project, residential solar batteries will be available to draw excess wind energy generation that cannot be transported to industrial regions due to grid capacity limitations or discharge energy when needed and to balance the power grid. The TenneT gets informed about available capacity from batteries by blockchain, and the batteries' contribution is recorded in the blockchain [147]. The second pilot project was in the Netherlands in collaboration with Vandebron company. In this project, Vandebron made EV batteries capacity available to be used by TenneT for grid balancing by controlling their charging and discharging. Blockchain was used to record the availability of each EV and its response to TenneT signal [124]. The household batteries and EV batteries capacities can enhance power system flexibility, enable RESs integration, and reduce RESs generation curtailment. After two years of the first pilot project launch, in May 2019, TenneT and Sonnen revealed that blockchain proved that it is a promising technology that may have an important role in grid transition. They intend to examine blockchain in other projects. They found that blockchain can enable decentralized, secure, and fast data exchange and fast and low-cost transactions. Therefore, blockchain can facilitate the participation of small DERs in providing grid services and their coordination with different system operators [148]. Moreover, in March 2020, Sonnen announced a project in Germany that uses energy storage devices distributed in houses to operate as VPP to absorb excess wind generation and decrease curtailment. EWC blockchain was used in this project [149]

Green Energy Wallet uses a blockchain-based platform that uses existing home batteries and EV batteries to provide balancing for the grid with renewable generation. The batteries will charge where there is excess generation from RESs, and the electricity price is low; and discharge when the energy is needed, and the electricity price is high, which ensures efficient use of renewable generation and reduce curtailment. The home batteries and EV owners are rewarded for their participation [150]. Electron company in the United Kingdom (UK) developed a blockchain-based platform that enables registering of distributed assets connected to the power grid. The asset data such as characteristics, type, capacity, and location are registered. This gives more visibility to system operators to the devices connected to the power grid and enables better forecasting and modeling and lower operation cost. In addition, the platform offers flexibility trading market. Electron has many projects in collaboration with system operators and energy companies [151]. Also, Electron collaborated with Our Power, IES, and London Business School in CEDISON project, which focuses on DR, energy trading, and local balancing in local energy communities. In this project, the blockchain was used as a platform for energy trading [152]. Moreover, a group of UK DSOs is investigating the potential of blockchain-based smart contracts in distribution system operation considering the potential change of DSOs' role [153].

In DR, the consumers change their consumption at peak times and receive rewards from the utility. The problem in DR schemes is that many times the consumers fail to meet the consumption reduction amount requested by the utility. In Japan, Fujitsu company with support from ENERES distribution company, used blockchain technology to improve DR. It developed a blockchain-based platform for trading energy shortages and surpluses between consumers. Using this technology, if a consumer is unable to meet the requested reduction in consumption from the utility, he can ask another consumer to provide this reduction in consumption in a P2P (i.e., consumer to consumer) manner. Also, the consumer can buy his energy requirement from a nearby prosumer. They tested this system using simulations, and it resulted in a 40% increase in the DR success rate [154].

It should be mentioned that blockchain technology must have extremely low latency and high throughput to enable real-time verifications and be suitable for grid operation and management applications. Also, a large amount of data about grid infrastructure, grid constraints, metering, communication, and control will be stored on the blockchain as have to be appropriately managed and protected from any cyberattack.

IV. SUMMARY AND DISCUSSION OF RESEARCH STUDIES, PROJECTS, AND STARTUPS

The previous section discussed eight blockchain-based use cases, and a large number of research studies, projects, and startups were presented to show the research and development activity in each application. This section presents a summary and comparison of research studies, projects, and startups discussed in the previous section. Table 4 summarizes many of the research articles discussed in the previous section, which propose blockchain-based solutions in the electricity sector. The studies are categorized and compared based on the application, objective, blockchain technology, blockchain functions, and involved actors. For all the studies, blockchain was used to primarily provide decentralization, disintermediation (i.e., reduce intermediaries), transparency, security, immutability, preserve identity and data privacy, and trust among actors. In addition to these primary functions, blockchain plays different functions in different applications. For P2P energy trading blockchain platform operated as a marketplace to match supply and demand bids using matching or trading algorithms (usually written as a smart contract), track and record energy production and consumption of all market participants, track trading of energy, and execute financial transactions (i.e., payments) in a secure, reliable, and low-cost manner. The actors involved in P2P energy trading are active consumers (i.e., prosumers) which have local generation, consumers, DSO or a retailer which supply energy to the community if there is an energy deficit and buy the surplus energy from the community, and microgrid operators which are the responsible authority for participation in P2P energy trading between microgrids. For wholesale electricity markets, the blockchain functions are matching bids, tracking trading of energy, and executing financial transactions similar to P2P energy trading. The actors involved in wholesale electricity markets are generators, market operator or system operator, consumers, and retailers.

For metering, billing, and retail markets application, the blockchain functions are decentralized recording of consumption data, executing payments, and automation of the whole metering and billing processes or other administrative processes such as switching between retailers. The involved actors are consumers, DSO, and retailers. For RECs and carbon credits trading, the blockchain platform operates as a marketplace to trade RECs and carbon credits where credits buyers and sellers can make offers, match bids and transfer the credits from seller to buyer, and execute payments. Moreover, by integrating blockchain with RESs smart meters, the issuance of RECs can be automated. The involved actors in this application are credit or certificate buyers (i.e., industrial entity, company, factory, etc.), credit seller (i.e., industrial entity, company, factory, renewable energy producer, etc.), authority, and auditor. Authority represents a government body that regulates the market and is responsible for issuing credits. The auditor assesses the entity emission rate. For EVs charging application, blockchain tracks and records EVs charging energy, execute payments, match bids between vehicles for P2P trading between EVs (i.e., V2V) using matching or trading algorithms (usually written as a smart contract), and using smart contracts to manage the charging and discharging of EVs. The involved actors in this application are the EV owners, charging station operators, aggregator, and local energy producers.

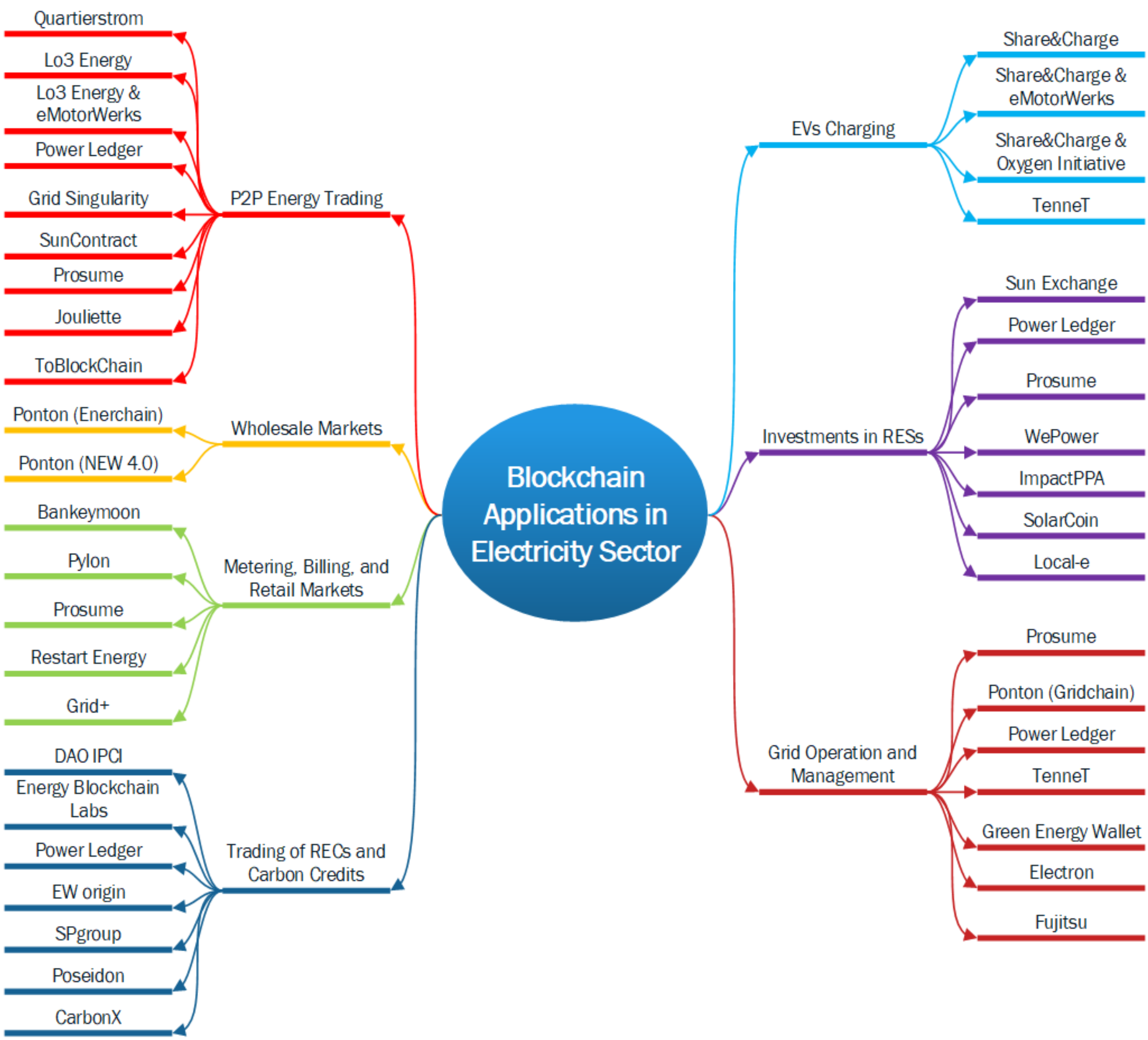

FIGURE 6. Projects and startups investigating blockchain applications in the electricity sector.

For enhancing power system cyber security application, the blockchain functions are secure and distributed data storage, detection of any malicious behavior to tamper with data, secure communication and data exchange between participants (i.e., connect actors), and by achieving all previous functions, it protects the system from cyber-attacks. The involved actors in this application are consumers and grid operator (i.e., DSO). For investment in RESs application, the blockchain functions are executing funding transactions and regular payments to investors. The actors involved are investors and building owners or plant owners. For grid operation and management application, blockchain tracks and record the production and consumption of all participants, connect actors by enabling secure data exchange and transactions, and execute payments. The actors involved here are active consumers (i.e., prosumers), consumers, DSO or a retailer, and aggregator.

Besides research studies, the previous section demonstrated that startups, companies, and utilities are making a great effort to develop blockchain-based solutions for electricity sector applications. Fig. 6 shows projects and startups investigating blockchain applications in different fields in the electricity sector. Also, table 5 summarizes the primary information about the blockchain projects and startups that are discussed in section III [8], [12], [15]. The table compares projects and startups in terms of type (i.e., pilot project, startup, etc.), country, blockchain platform used for implementation, consensus mechanism, application, and foundation year or year of project implementation. It can be seen that startups have most of the effort in developing blockchain-based applications in the electricity sector, and incumbents (i.e., utilities, system operators, etc.) try to cope with the blockchain technology developments by pilot projects and alliances with startups [155].

It could be noticed that many studies and projects used public blockchain networks such as Ethereum to assess the technical suitability of blockchain for many applications. However, public blockchain networks may not be suitable for many electricity sector applications due to high and variable transactions cost, low throughput, and transaction confirmation latency. These issues question the suitability of public blockchain networks for many electricity sector applications that require a large number of micro transactions and continuous data exchange. Moreover, all transactions and data exchange in the public blockchain is accessible for any network participants, which makes it unpreferable for electricity sector applications that require access control on the data and transactions. Therefore, private and consortium blockchain seem more suitable for many electricity sector applications due to its low transactions cost, high throughput, low latency, and control of access and validation of transactions and data. However, private and consortium blockchains are less decentralized than public blockchains, which limits capturing the full potential of blockchain decentralization features. In other words, private and consortium blockchain reduce decentralization, censorship resistance, immutability, and security [156]. Furthermore, new DLTs such as IOTA promise to tackle a few of these public blockchain challenges. IOTA promises no transaction fees, high throughput, and low latency. However, IOTA is still under development and not mature yet.

It can be seen that recent blockchain-based solutions developed for electricity sector applications prefer the use of private and consortium blockchain over the public blockchain. They are also suitable to the nature of the electricity sector, where few central operators cannot be eliminated because they are responsible for keeping the system operating within acceptable limits. For instance, P2P trading was proposed in previous studies where neighbors in a community can freely trade with each other directly. However, in reality, DSO has to check if the energy trading can be done or not depending on the grid status, which means that DSO cannot be eliminated from the P2P trading process. Therefore, we believe that blockchain full decentralization of the power system is difficult practically, but it can enable a less centralized power system where blockchain can strengthen the role DERs and small consumers in managing the power system and participation in grid-wide markets and weaken the role of central operators.

Previous studies, industrial projects, and startups focused on proposing blockchain-based solutions for individual applications (i.e., P2P energy trading, automatic issuance and trading of RECs, microgrid operation and management, interaction between different power system participants (i.e., TSO, DSOs, aggregators, etc.), etc. Future studies should consider how blockchain can combine more than one of these applications at the same blockchain network because in reality, most of these applications are in the same system and may have common or conflicting objectives. Another scenario is to consider the interaction and communication between different blockchain networks that provide different functions. By doing this, the individual applications can be combined using blockchain to form a decentralized or less centralized electricity sector.

It is not easy to evaluate the suitability of blockchain technology for different sectors and specific applications in each sector. Therefore, many studies and projects are implemented to investigate the suitability of blockchain for different applications and assess its added value and implementation challenges. Few studies developed preliminary evaluation criteria that can help in deciding if blockchain technology is required for a specific application or other traditional technologies such as databases are more suitable [157], [158]. Fig. 7 shows a flow chart that presents a guiding framework in order to decide if blockchain is required for an application. It can be seen that blockchain can be suitable if: first, there are problems or issues with authorizing a trusted authority or central operator to manage the system and validate transactions and data. Second, there is a need for transparency of data and transactions, and a need for immutable data storage. Third, there is a need for multiparty participation in managing the system, sharing data, and writing on the ledger (i.e., validating transactions). Finally, some players are not known or trusted and may have conflicting interests. If all players are not known, permissionless blockchain is more suitable (i.e., DERs allowed to validate transactions). If all players are known and trusted (i.e., TSO, DSOs, aggregators, etc.), a database with a shared validation right can be used. However, permissioned blockchain can still hold value by combining many processes (i.e., data storage, data sharing, financial transactions, etc.) and provide trust between participants. Moreover, permissioned blockchain is more suitable than permissionless blockchain if high performance (i.e., high transactions processing rate and low energy consumption) is required. Depending on the transparency level required, private permissioned blockchain can be used if the public access to transactions records is limited, and public permissioned blockchain can be used to allow the public to access transactions records.

V. BLOCKCHAIN CHALLENGES AND POTENTIAL SOLUTIONS

Blockchain technology passed the proof of concept phase and proved its potential for many applications in different sectors. However, it has some limitations, barriers, and challenges that should be tackled for the large adoption of this technology [11]. It should be considered that blockchain is in its infancy, and many of the following issues are expected

TABLE 4. **Summary of research articles for blockchain-based applications in the electricity sector.**

Ref.	Application	Objective	Blockchain technology	Blockchain functions: Match bids	Blockchain functions: Track energy trading	Blockchain functions: Execute payments	Blockchain functions	Actors: Active consumers	Actors: Consumers	Actors: DSO/ Retailer	Actors: Microgrid operators
[67]	P2P energy trading	Develop a blockchain-based LEM in a small community that allows prosumers and consumers to trade electricity	Ethereum	X	√	√		√	√	√	X
[68]	P2P energy trading	Investigate IOTA DLT platform for P2P energy trading and overcoming blockchain weaknesses. The simulation results showed the feasibility of IOTA for creating platforms for P2P energy trading	IOTA (DLT)	√	√	√		√	√	√	X
[70]	P2P energy trading (between microgrids)	Develop a blockchain-based mechanism for multi-directional P2P energy trading between microgrids. The results showed that the proposed mechanism increased RESs utilization and microgrids' profits.	Ethereum	√	√	√		√	√	√	√

Ref.	Application	Objective	Blockchain technology	Blockchain functions: Match bids	Blockchain functions: Track energy trading	Blockchain functions: Execute payments	Blockchain functions	Actors: Generators	Actors: Market operator /system operator	Actors: Consumers	Actors: Retailers
[86]	Wholesale Markets	Develop a Blockchain-based wholesale market considering the Australian wholesale market as a case study.	Hyperledger	√	√	√		√	√	√	√
[87]	Wholesale Markets	Propose a Blockchain-based solution to enhance the automation of balancing market, reduce the delay of imbalance prices publication, and fast financial transactions.	Ethereum	X	√	√		X	√	√	√

Ref.	Application	Objective	Blockchain technology	Blockchain functions: Track energy	Blockchain functions: Execute payments	Blockchain functions: Automate processes	Blockchain functions	Actors: Consumers	Actors: DSO	Actors: Retailers	Actors
[90]	Metering, billing, and retail markets	Develop a blockchain-based prototype for metering and billing to preserve consumers' data privacy, reduce vulnerability to cyber-attacks, and automate processes.	Hyperledger	√	√	√		√	X	√	
[91]	Metering, billing, and retail markets	Develop a prototype for a decentralized and secure recording of power consumption of residential consumers using blockchain and IoT. This proposal aims to test the feasibility of blockchain and IoT in this application.	Ethereum	√	√	√		√	X	√	
[95]	Metering, billing, and retail markets	Develop a proof of concept of a blockchain-based system for switching between retailers. The proposed system aims to facilitate the process of switching between retailers by automating all the processes.	Ethereum	X	X	√		√	√	√	

Ref.	Application	Objective	Blockchain technology	Blockchain functions: Automatic issuing of credits	Blockchain functions: Immutable record of credits	Blockchain functions: Match bids	Blockchain functions: Execute payments	Actors: Credits buyers	Actors: Credits sellers	Actors: Authority	Actors: Auditor
[98]	Carbon market	Propose a blockchain-based ETS. In this ETS, no central organization is needed to manage bids and offers of participants. The proposed ETS can enhance traditional ETSs efficiency and tackle management and fraud issues.	Multichain	X	√	√	√	√	√	√	√
[99]	Carbon market	Investigate the application of blockchain technology in existing carbon markets, focusing on the Australian carbon market as a case study. The study presented the design process. The study showed that blockchain could improve the carbon market performance and efficiency, reduce transaction costs, and increase transparency and equity.	NA	X	√	√	√	√	√	√	√
[100]	RECs market	Propose a blockchain-based RECs market that allows direct transactions between producers and consumers. The results showed that blockchain could be used to create a robust platform for RECs trading with low operating costs.	Ethereum	√	√	√	√	√	√	√	X

Ref.	Application	Objective	Blockchain technology	Blockchain functions: Track energy	Blockchain functions: Execute payments	Blockchain functions: Match bids	Blockchain functions: Control charging/ discharging	Actors: EV owners	Actors: Charging station operators	Actors: Aggregator	Actors: Local producers
[110]	EVs charging	Propose a blockchain-based EVs charging with low computation	Hyperledger	√	√	X	X	√	√	X	X

TABLE 4. ***(Continued.)*** **Summary of research articles for blockchain-based applications in the electricity sector.**

		and communication costs and security against attacks									
[111]	EVs charging	Practical implementation of IoT-blockchain system to handle EVs charging from public chargers	Ethereum	√	√	X	X	√	√	X	X
[113]	EVs charging	Propose a secure blockchain-based EVs charging scheme in a smart community that maximizes operator profit and satisfy EVs preferences	Permissioned DBFT	√	√	X	√	√	√	√	√
[114]	EVs charging	Develop a blockchain smart contract request charging offers from nearby EVs charging stations and selects a suitable one based on the charging price	Ethereum	√	√	√	X	√	√	X	X
[116]	EVs charging	Propose a blockchain-based demand response that incentivizes EVs to discharge energy and provides a local balance between supply and demand	Consortium	√	√	√	√	√	√	√	X
[117]	EVs charging	Propose a blockchain-based management system for EVs battery swapping to solve the trust issue between charging stations and EV owners.	Ethereum	X	√	X	X	√	√	X	X
[118]	EVs charging	Develop a laboratory prototype of an IoT-blockchain based management system for EVs battery swapping	Ethereum	X	√	X	X	√	√	X	X
Ref.	**Application**	**Objective**	**Blockchain technology**	**Blockchain functions**				**Actors**			
				Monitor grid/ data storage	Detect malicious behavior	Connect actors	Cyber-attack protection	Consumers	DSO		
[129]	Power system cyber security	Presents the concepts of two possible scenarios of cyber-attacks, 1) generation level and 2) distribution level. In these scenarios, blockchain will work as a secondary control to minimize the power outages or losses caused by the cyber-attack. Blockchain functions and actors of the second scenario are considered.	NA	√	√	√	√	√	√		
[131]	Power system cyber security	Propose a privacy-preserving, secure, and distributed data aggregation method for aggregating smart meters data. The proposed method used homomorphic encryption and blockchain.	PBFT	√	√	√	√	√	√		
[132]	Power system cyber security	Propose a blockchain-based data aggregation and regulation mechanism for smart grid.	Consortium	√	√	√	√	√	√		
Ref.	**Application**	**Objective**	**Blockchain technology**	**Blockchain functions**				**Actors**			
				Funding transactions	Payments to investors			Investors	Building owners	Plant owners	
[133]	Investment in RESs	Proposed the idea of DLT based crowdfunding for offshore wind farms	No	√	√			√	X	√	
[134]	Investment in RESs	Proposed an IOTA-based crowdfunding platform for residential PV projects to reduce LCOE and financial costs.	IOTA	√	√			√	√	X	
Ref.	**Application**	**Objective**	**Blockchain technology**	**Blockchain functions**				**Actors**			
				Track energy	Execute payments	Connect actors		Active consumers	Consumers	DSO/ Retailer	Aggregator
[142]	Grid operation and management	Propose a blockchain-based LEM managed by an aggregator operating as a VPP. In this market, small prosumers and consumers were allowed to sell and buy electricity and provide services to the power system.	Hyperledger	√	√	√		√	√	√	√
[143]	Grid operation and management	Develop a blockchain-based decentralized energy management system for a community containing local RESs and smart buildings without the need for a central entity like an aggregator.	Ethereum	√	√	√		√	√	√	X
[144]	Grid operation and management	Investigates the use of blockchain for economic and technical management of a microgrid. The blockchain tracks the active power trading and reactive power injection and executes the corresponding financial transactions.	Tendermint	√	√	√		√	√	√	X

to be tackled by innovative future developments. Similarly, blockchain applications in the electricity sector are at an early stage of research and development since it began in 2016 [5]. This section presents the main challenges that face blockchain technology in general and the challenges for blockchain adoption in electricity sector applications. Fig. 8 lists the challenges of blockchain technology that delay its large-scale adoption.

A. GENERAL CHALLENGES OF BLOCKCHAIN TECHNOLOGY

1) HIGH ENERGY AND COMPUTATIONAL POWER REQUIREMENTS

The first challenge of blockchain is high resources requirements (e.g., energy consumption and computational power). The use of the PoW consensus mechanism enhances the security of blockchain because the hacker needs to have more

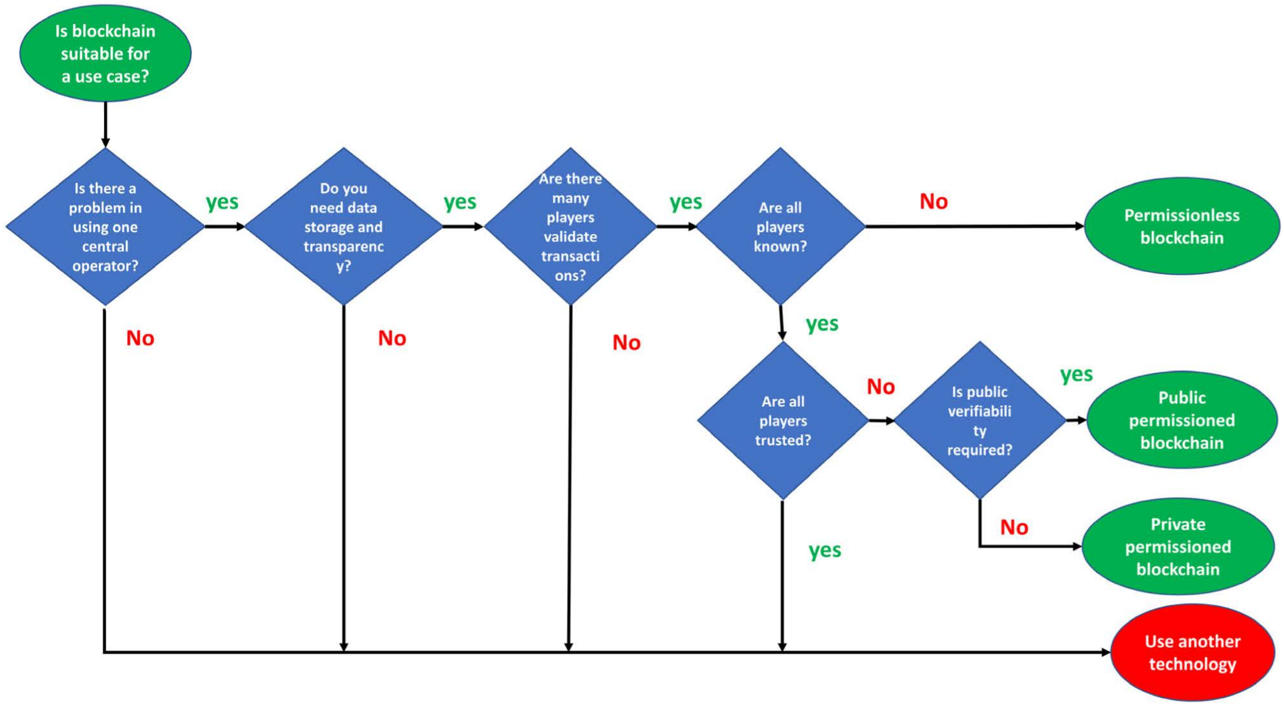

FIGURE 7. Preliminary evaluation criteria for suitability of blockchain technology to an application.

computational power than all other participants (i.e., 51% of computational power), which is economically unviable for hackers and difficult to achieve. On the other hand, for PoW, there is a need for expensive hardware with high computational power to solve the hash puzzle, and it consumes a large amount of electrical energy. This means a high capital cost for buying computation hardware and a high running cost for high electricity bills [160], which minimize blockchain economic benefits. Moreover, it will have a negative environmental impact due to the high consumption of energy mainly produced by nonrenewable generation [160]. However, these issues of PoW can be tackled by other consensus algorithms like PoS, PoAu, PBFT, and other recently developed consensus mechanisms, which need less computational power and electricity consumption [161]. Ethereum is planning to use the PoS consensus mechanism instead of PoW due to the discussed issues.

2) LATENCY AND LOW THROUGHPUT

Latency is a big issue in blockchain technology; for example, Bitcoin takes 10 minutes to verify and settle transactions and add them to the new block and 60 minutes for final confirmation. This feature can be suitable for some applications like financial transactions but not suitable for applications like the electricity sector with low latency requirements (i.e., real-time) or IoT applications where there is a continuous interaction between devices. In addition, the throughput (i.e., transactions processing rate) is very small in many widely used blockchain platforms, about seven per second for Bitcoin and 15 per second for Ethereum, while other payment methods such as VISA can process thousands of transactions per second. Latency and low throughput issues are mainly encountered in public blockchains that operate in a trustless environment, and they can be solved in private and consortium blockchains by the use of fast consensus algorithms such as PoAu. Moreover, to improve public blockchain performance, many studies combine the consensus mechanism of public blockchain with a fast private blockchain consensus mechanism [162]. The author of [163] proposed a hybrid blockchain that can combine public blockchain security and private blockchain efficiency. Furthermore, new DLTs such as IOTA promise a high throughput and low latency; however, it is still under development and not mature compared to blockchain technology.

3) LARGE DATA STORAGE

For public blockchain networks, there is a large number of new transactions executed every day and added to the blockchain network, which increases the storage cost because all the main nodes have to keep an updated copy of all the transactions and data stored in the blockchain. One of the proposed solutions is to use sidechains to store the data and use the main blockchain only as a control layer instead of using it as a storage layer [164], [165].

4) FORKS

For the current blockchain applications like Bitcoin and Ethereum, any change or upgrade in the code of the blockchain network must be approved by consensus mechanisms. Any disagreement or conflict will lead to hard forks

TABLE 5. Summary of blockchain-based projects and startups in the electricity sector discussed in this article.

#	Project or company	Type	Country	Platform	Consensus mechanism	Application	Year Founded
1	Bankymoon	Startup	South Africa	Ethereum	PoW	Metering and billing	2015
2	CarbonX	Startup	Canada	Ethereum	PoW	Trading of RECs and carbon credits	2017
3	DAO IPCI	Private project (non-profit)	Russia	Ethereum	PoW	Trading of RECs and carbon credits	2016
4	Electron	Startup	UK	EWC	PoW, PoAu	Grid operation	2015
5	Energy Blockchain Labs	Company	China	Hyperledger	PBFT	Trading of RECs and carbon credits	2016
6	EW Origin	DApp running on EWC	Germany	EWC	PoAu	Trading of RECs and carbon credits	2018
7	Fujitsu	Patent by company and utility	Japan	NA	NA	Grid operation	2018
8	Green Energy Wallet	Startup	Germany	NA	NA	Grid operation	2017
9	Grid Singulaity	Startup	Austria	EWC	PoAu	P2P energy trading	2016
10	Grid+	Startup	US	Ethereum	PoW	Retail markets	2017
11	ImpactPPA	Startup	US	Ethereum	PoW	Investment in RESs	2017
12	LO3 Energy	Startup	US	Tendermint	PBFT	P2P energy trading	2016
13	Lo3&eMotorWerks	Pilot by companies	US	Tendermint	PBFT	P2P energy trading	2018
14	Local-e	Startup	US	Ethereum	PoW	Investment in RESs	2017
15	Ponton (EnerChain)	Pilot by a company	Germany	Tendermint	PBFT	Wholesale markets	May 2016 -Mar 2018
16	Ponton (GridChain)	Pilot by a company	Germany	Tendermint	PBFT	Grid operation	2016
17	Ponton (New 4.0)	Pilot by a company	Germany	Tendermint	PBFT	Wholesale markets	2017
18	Poseidon	Startup	Switzerland	Stellar [160]	Federated Byzantine Agreement	Trading of RECs and carbon credits	2017
19	Power Ledger	Startup	Australia	Ethereum	PoAu	P2P energy trading, Grid operation, Trading of RECs and carbon credits	2016

TABLE 5. ***(Continued.)*** **Summary of blockchain-based projects and startups in the electricity sector discussed in this article.**

20	Prosume	Startup	Switzerland	NA	NA	P2P energy trading, Grid operation, Investment in RESs, Metering and billing	2016
21	Pylon	Startup	Spain	Pylon Coin CORE	Proof of Capacity	Metering and billing	2017
22	Quertierstrom	Pilot project	Switzerland	Tendermint	PBFT	P2P energy trading	Jan 2019 – Jan 2020
23	Restart Energy	Company	Romania	NA	NA	Retail Markets, P2P energy trading	2015
24	Share&Charge	Startup	Germany	Ethereum/ EWC	PoW/ PoAu	EV charging	2016
25	Share&Charge and eMotorWerks	Startup	US	Ethereum/ EWC	PoW/ PoAu	EV charging	2017
26	Share&Charge and Oxygen Initiative	Startup	US	Ethereum/ EWC	PoW/ PoAu	EV charging	2017
27	SolarCoin	Startup	Andorra	SolarCoin (LiteCoin & Vericoin-based)	Proof of Stake Time	Investment in RESs	2014
28	SP group	Platform from utility	Singapore	EWC	PoAu	Trading of RECs and carbon credits	2018
29	Spectral (Jouliette)	Startup	Netherlands	MultiChain	PoW	P2P energy trading	2017
30	SunContract	Startup	Slovenia	NA	NA	P2P energy trading	2016
31	Sun Exchange	Startup	South Africa	Ethereum	PoW	Investment in RESs	2015
32	TenneT	Pilot by utility	Netherlands	Hyperledger	PBFT	Grid operation	2017
33	ToBlockChain	Startup	Netherlands	NA	NA	P2P energy trading	2016
34	WePower	Startup	Gibraltar	Ethereum	PoW	Investment in RESs	2017

creation. Hard fork refers to the state blockchain network split into different chains that operate by different rules. A hard fork occurred in the Bitcoin network after a conflict in the block size resulted in two chains with different coins, traditional Bitcoin (i.e., BTC) coin with 1 MB block size and Bitcoin Cash (i.e., BCH) coin with 8 MB block size [166]. Forks occurred in other blockchain networks such as Ethereum [167]. Therefore, there is a concern about the lack of modification flexibility in the blockchain.

5) ERROR CORRECTION INABILITY

One of the main advantages of public blockchain is immutability, which means the inability to make changes in blockchain data or transactions in the created blocks. This advantage ensures blockchain integrity and tamperproof and is usually viewed as a strength. However, it eliminates the ability to correct errors or make modifications in previous blocks if needed. For instance, if there are bugs or errors in a smart contract stored in the blockchain, it may result in severe consequences similar to what happened in the DAO

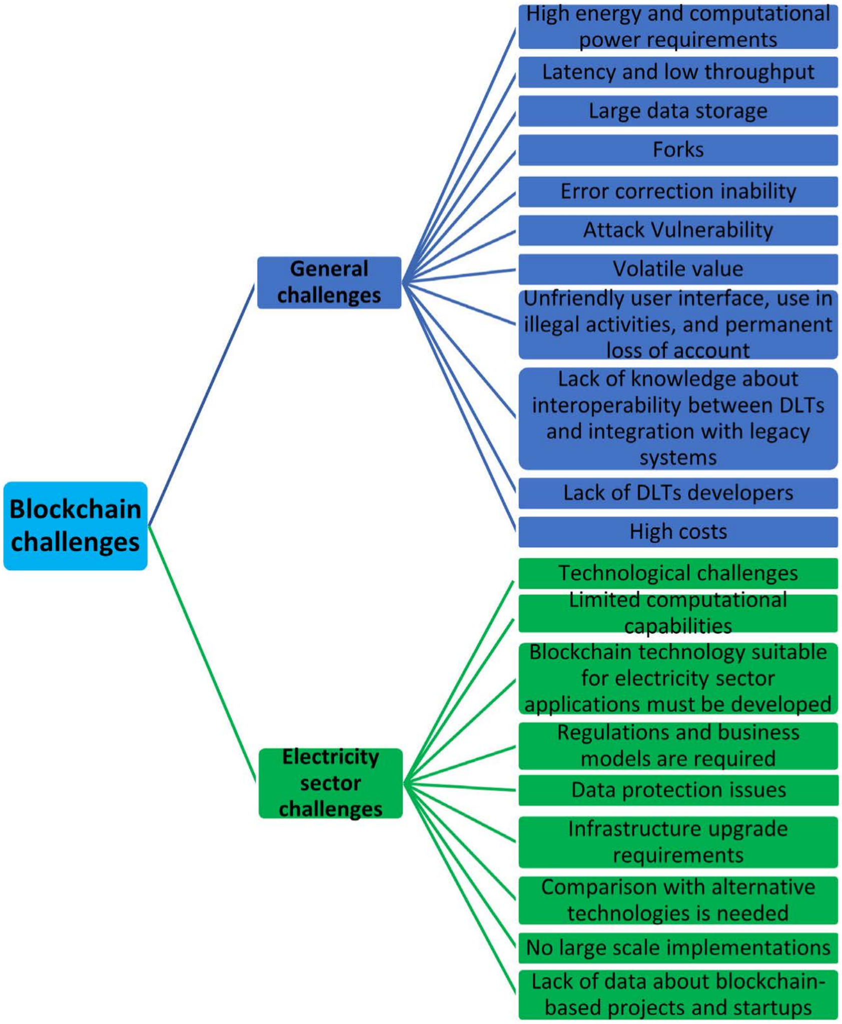

FIGURE 8. Challenges of blockchain technology that delay its large-scale adoption.

attack [168], [169], and the solution was to hard fork the Ethereum network. Therefore, public blockchain technology is not suitable for applications that require modifications and updates on previous data or transactions. Private and consortium blockchain enable transactions modification to some extent [27].

6) ATTACK VULNERABILITY

Blockchain is proposed as a secure, attack-resistant, immutable, and tamper-proof technology. However, this security feature is not completely proven yet because blockchain is still not attractive to attackers and did not receive many attacks yet to guarantee the claimed security and tamper-proof features. In reality, there is a possibility of manipulating and changing block data by malicious users if they gain control of 51% of computation capacity in case of PoW or 51% of the network stakes in case of PoS (i.e., 51% attack) [170]. Gaining control of 51% of the network allows the attacker to reverse transactions, prevent confirmation of normal transactions, modify transaction orders, and others. Currently, in Bitcoin, many mining nodes are combining their computational power, forming mining pools that represent a form of centralization. These mining pools may form a risk of making a malicious attack if they control enough computation capacity [171]. Moreover, as the technology is still in early stages of development, there is a possibility of malfunction if used for large-scale applications.

7) VOLATILE VALUE

The blockchain-based cryptocurrencies' value is very volatile, and they got affected by many events that represent a risk for people's investments in cryptocurrencies and uncertainty for blockchain network users and blockchain-based applications. For instance, in Ethereum public chain in order to make any transaction or execute any smart contract, a fee (i.e., gas) has to be paid to the miners. The volatility in the gas price makes the fees for any service provided by blockchain-based smart contract or transactions execution variable and unpredictable. Moreover, the transactions take a longer time to be validated when there is a high activity in the blockchain network [120]. Also, the fee paid to the miners represents a burden for applications that involve microtransactions, such as IoT [172]. These issues are mainly in public blockchains and can solve in private and consortium blockchains, which have better performance (i.e., higher throughput, lower latency) and lower transaction fees. Moreover, other DLT platforms that are still under development promise zero fees transactions, such as IOTA.

8) THE UNFRIENDLY USER INTERFACE, USE IN ILLEGAL ACTIVITIES, AND PERMANENT LOSS OF ACCOUNT

Blockchain technology is under development, and its platforms are not user-friendly till now. As a result, it is difficult for the ordinary person to use blockchain platforms which results in delaying and limiting the wide adoption of the technology. Moreover, with the pseudonymous nature of public blockchain platforms such as Bitcoin that do not require any personal information (name, phone number, email, etc.) to have an account, there is a possibility that criminals can use it for illegal activities. Furthermore, for public blockchains that are not controlled by a central entity, by losing or forgetting the wallet password (i.e., access key or the private key), the money (i.e., cryptocurrencies) will be lost, and there is no way to recover it [173]. Several solutions to this issue are being developed [174].

9) LACK OF KNOWLEDGE ABOUT INTEROPERABILITY BETWEEN DLTS AND INTEGRATION WITH LEGACY SYSTEMS

Currently, there are many developments of different DLTs with different features (i.e., network management, consensus mechanism, data management, etc.) and research for assessing the strengths and weaknesses of each of them and their suitability for different applications. However, there is a lack of research on how different DLTs can interact with each other in the future, considering that different applications may use different DLTs? Additionally, how DLTs could be integrated with other technologies (i.e., legacy systems) that are being used now [175]?

10) LACK OF DLTs DEVELOPERS

There is a significant interest in blockchain technology or DLTs from academia and industry. However, as the case with any new technology, there is a lack of professional DLTs developers currently [175], which could delay the technology development and adoption in various sectors. Therefore, there is a need to offer training and courses by universities for blockchain technology [176]. Many prestigious universities and education platforms are offering courses and programs for blockchain technology on-campus and online [177], [178].

11) HIGH IMPLEMENTATION COSTS

Although blockchain can provide many interesting features, currently, it has a higher implementation cost than other existing alternative solutions that are more mature and have a better performance. That is why blockchain is not more cost-effective than other technologies yet. However, we should consider that future development of blockchain and other DLTs may provide a better performance, lower implementation costs, and added value that outweigh the implementation costs, which can encourage wider adoption of the technology.

B. CHALLENGES FOR BLOCKCHAIN ADOPTION IN THE ELECTRICITY SECTOR

1) TECHNOLOGICAL CHALLENGES

As described in section V.A, blockchain technology still has many technical challenges. Many of these challenges represent a barrier to blockchain adoption in electricity sector applications, such as high energy and computational power requirements, latency, low throughput, limited computational capabilities, etc. These challenges should be tackled to adopt blockchain in many electricity sector applications.

2) LIMITED COMPUTATIONAL CAPABILITIES

Most of the blockchain applications in the electricity sector depend on the capabilities provided by smart contracts. However, the high cost of performing computations on blockchain and the lack of some mathematical functions limit the computations that can be done on the blockchain. Therefore, many studies try to perform simple computations on the blockchain or perform the complex and costly computations outside the blockchain, and their outputs are entered into the blockchain as inputs. Therefore, there is a need to develop solutions that enable complex computations on blockchain [42]. Most of the studies proposing blockchain-based solutions in the electricity sector applications do not calculate the cost of running smart contracts on blockchain [42]. Ref. [179] highlighted that the cost could be non-negligible. Therefore, future research should calculate the cost of running smart contracts, and the benefits must outweigh the cost.

3) BLOCKCHAIN TECHNOLOGY SUITABLE FOR ELECTRICITY SECTOR APPLICATIONS MUST BE DEVELOPED

There are many challenges and barriers to blockchain applications in the electricity sector. Most of the studies and projects of blockchain applications in the electricity sector are using blockchain platforms such as Ethereum or other blockchain platforms with features that are not suitable for many electricity sector applications requirements (i.e., low transactions processing rate, latency, high transactions cost, etc.). Using these general-purpose blockchain platforms makes it difficult to accurately evaluate the suitability and the added value of blockchain for electricity sector applications. Therefore, there is a need for blockchain technology (i.e., platforms) developed for electricity sector applications and even developed for a specific application in the electricity sector. By doing this, the actual benefits of integrating blockchain in the electricity sector can be assessed [180]. Also, the requirements of different electricity sector domains are diverse. As a result, there is a need for comprehensive studies for blockchain applications in each use case to compare different blockchain technologies or DLTs to know the most suitable technology for each application. Many companies and utilities are developing their own blockchain technology with features (i.e., network management (public, private, or consortium), consensus mechanism (PoW, PoS, PBFT, PoAu, etc.), data management (on-chain or off-chain), etc.) suitable for the application to capture the full potential of blockchain.

4) REGULATIONS AND BUSINESS MODELS ARE REQUIRED

Regulation is a significant barrier to blockchain adoption in many of the electricity sector applications discussed in section III [8]. For instance, while in some countries, regulations enable the active participation of consumers by installing local generation or storage, they do not enable big changes in power system frameworks like P2P energy trading or the use of DLTs within existing systems which obstruct large scale implementations of similar applications regardless of the level of technology readiness [13]. Therefore, there is a need for new electricity market regulations allowing LEMs and energy exchange at a local level in addition to enabling DERs to participate in grid-wide energy and ancillary services markets. Additionally, regulations organizing the use of blockchain for different electricity sector applications are required. These barriers will delay the adoption of blockchain technology by energy companies which tend to wait for technology development and regulation to emerge before investing. Furthermore, most studies and pilot projects evaluating blockchain applications in the electricity sector focus on deregulated electricity markets. Therefore, more attention should be given to blockchain applications in the electricity sector, considering regulated or partially deregulated electricity markets and evaluating the added value it can provide because in these markets, a higher impedance to the adoption of new technologies is expected compared to deregulated markets [13].

Moreover, there is a need to develop innovative business models that define the new rules and responsibilities for all stakeholders participating in these applications [8]. For instance, in LEMs, the DSO responsibilities will decrease, and DSO may work as a supervisor for the energy trading to make sure grid constraints are not violated. The business models will define the payment that DSO will receive for using the grid infrastructure that he owns. TSO can be engaged in this also if the energy trading is between DSOs and the transmission system is used. Another scenario is when DERs provide a service to the TSO, the DSO should be rewarded for using his grid infrastructure to deliver the service, and the DSO will be an important stakeholder in defining if the service can be provided or not depending on the distribution network constraints.

5) DATA PROTECTION ISSUES

Blockchain technology enables the network participants to have an immutable copy of data, and it could be open to anyone to access in the case of the public blockchain. This feature represents an issue for many data protection regulations [42], [181]. For instance, the General Data Protection Regulation (GDPR) introduced principles that are relevant to blockchain technology applications in the electricity sector [182]. The principles assume that the data should be kept with a minimum number of copies, the ability to modify or remove data, and the presence of a legal person to manage sensitive data. These principles could affect the application of blockchain in many electricity sector applications considering the sensitive data of different stakeholders that will be stored on the blockchain. Therefore, more research is needed to find ways to fulfill GDPR requirements in electricity sector applications.

6) INFRASTRUCTURE UPGRADE REQUIREMENTS

The wide adoption of Blockchain technology in the smart grid requires expensive infrastructure upgrades in terms of ICT suitable for blockchain operations and changes in the smart meters. For instance, in the Quartierstrom project, a LEM for trading energy in a community, they needed a smart meter with an application processor that was not available in smart meters in the market [74]. Moreover, smart meters with suitable time resolution should be installed, which means additional investments and taking some time to install them nationally. Furthermore, Ref. [183] found that P2P energy trading requires ten times communication bandwidth compared to real-time smart metering in centralized management systems. The results of the Quartierstrom project showed that blockchain-based LEM required communication technologies with a data rate of more than 1000 kbit/s, which makes some communication technologies unsuitable for this application due to their limited data rate [184]. This cost may discourage or delay utilities adoption of blockchain or large-scale implementations of applications such as P2P energy trading unless the benefits outweigh the costs.

7) COMPARISON WITH ALTERNATIVE TECHNOLOGIES IS NEEDED

It was noticed that most of the research studies and projects try to prove that blockchain technology or DLTs can be used in a specific application, and there is no obvious and objective comparison with the other available technology that can do the same task. In addition, there is no clear discussion of the added value of blockchain over other technologies. Therefore, in order to convince decision-makers and investors about blockchain, there is a need for comprehensive studies comparing blockchain and other technologies applied at each potential application to prove it is added value over other solutions. Future studies and pilot projects should perform a techno-economic assessment of the blockchain technology for different applications and compare it with other alternative technologies. A recent study [185] compared the performance of blockchain technology and a central database for the operation of LEM, which is considered the most promising application of blockchain technology in the electricity sector. They found that blockchain-based LEM required computational time 144 times larger than LEM for 50 bids. Moreover, they found that blockchain-based LEM has reliability and scalability issues compared to central LEM. They claim that the blockchain technology in the current development state does not add much value to LEMs. Therefore, future studies should compare blockchain technology and DLTs with other alternative technologies for each electricity sector application in terms of technology readiness, performance, implementation costs, etc.

8) NO LARGE-SCALE IMPLEMENTATIONS

Blockchain's future in the electricity sector is unsure. The technology proved its applicability to many applications in the electricity sector in studies, pilot projects, and startups, but it is still in the proof of concept phase and has no large-scale implementations. Additionally, the technology is facing many challenges like low transactions processing rates, high transaction fees [120], regulation, and legal barriers. More studies and highly developed large-scale implementations are required to convince governments, investors, decision-makers, and regulators of the technology's benefits and before its potential in the electricity sector becomes certain and obvious [121].

9) LACK OF DATA ABOUT BLOCKCHAIN-BASED PROJECTS AND STARTUPS

In this paper, many pilot projects and startups developing blockchain-based applications in the electricity sector are introduced, which is positive from technology development and understanding perspective. It was noticed that they promote blockchain technology and give many details about the benefits the blockchain can provide. However, very limited details are given about the challenges for practical implementation and drawbacks of using blockchain for a specific application. For instance, information on blockchain energy consumption, scalability, integration with other technologies used in the whole power system, etc. Therefore, we cannot be fully certain about the benefits they claim and the potential of blockchain for a specific application unless we know the challenges and the whole cost of using blockchain technology for this application.

VI. CONCLUSION

This article reviews the blockchain potential applications in the electricity sector. The review shows that huge efforts are being made by research institutions, startups, companies, and utilities to investigate the potential of blockchain technology in the electricity sector and the benefits that this new technology can provide. The blockchain applications in the electricity sector were classified into eight applications according to the field of activity. Many research studies, projects, and startups were presented to show the research and development activity in each application. The discussed blockchain-based applications used blockchain technology to optimize existing processes like metering and billing, retail markets, wholesale markets, or grid management and using blockchain for emerging applications like P2P energy trading.

The findings of the research studies and industrial effort showed the promising potential of blockchain technology in electricity sector applications and the added value it can provide. It was found that blockchain could potentially provide several benefits, such as 1) increasing the role of final consumers and offering them many choices such as choosing supplier and energy origin. 2) decentralized grid operation and management. 3) decentralized electricity markets structures. 4) enable participation of DERs in electricity markets and provide grid services. 5) automate many processes using smart contracts. 6) enhance transparency. 7) improve security against cyber-attacks and malicious behavior. 8) eliminate single point of failure. 9) preserve the privacy of participant ID and data. 10) provide trust between participants with no need for a third-party intermediary. 11) low-cost financial transactions and data exchange. However, it was found that most of the studies and projects of blockchain applications in the electricity sector are based on simulations, and small pilot projects of field implementations to provide proof of concept and investigate blockchain capabilities and large-scale implementations are still missing due to many barriers and challenges of using blockchain in these applications. The main barrier is the absence of regulations organizing potential applications such as P2P energy trading and technological challenges. Other challenges that blockchain technology must tackle to achieve wide adoption in different sectors and the electricity sector specifically were discussed in detail.

Most of the reviewed studies and projects that were performed in previous years focused on investigating the applicability of blockchain for different applications, which is not enough for assessing the suitability of blockchain for a specific application. Therefore, future studies should focus on comparing blockchain technology and DLTs with other alternative technologies for each application in terms of technology readiness, performance, infrastructure upgrade requirements, implementation costs, business models, required regulations, etc. Additionally, the studies of each application should compare different blockchain-based solutions in terms of network management (i.e., public, private, and consortium), consensus mechanism (PoW, PoS, PBFT, PoAu, etc.), data management (i.e., on-chain and off-chain), etc. and define the most suitable combination for a specific application. This can help to develop efficient blockchain platforms tailored for a particular application.

We should consider that most of the companies developing a blockchain-based solution for the electricity sector were founded starting from 2016, which shows the early stage of this technology in electricity sector applications. As a result, there is room for many developments and investigations of blockchain technology solutions for electricity sector applications. Based on the current status of blockchain technology adoption in the electricity sector, the highly optimistic claims about the potential for the technology roles are still just expectations and are not supported by results from successful large-scale implementations. Therefore, the future of blockchain technology in the electricity sector is still an open question that will be answered based on new regulations, new business models, future studies and pilot projects, large-scale implementations, and blockchain technology or DLTs developments.

NOMENCLATURE

List of abbreviations used in this paper

ABCI	Application Blockchain Interface
BR	Balance Responsible Partie
DApp	Decentralized Applications
DERs	Distributed Energy Resources
DL	Distributed Ledger Technolog
DR	Demand Respons
DS	Distribution System Operator
ETSs	Emission Trading Schemes
EV	Electric Vehicle
EV	Ethereum Virtual Machine
EW	Energy Web Chain
EW	Energy Web Foundation
EW	Energy Web Token
FP	Fast Probabilistic Consensus
G2	Grid to Vehicl
GH	Greenhouse gas
GDPR	General Data Protection Regulation
HD	Hierarchical Deterministic
ICOs	Initial Coin Offerings
IC	Information and Communication Technology
IE	International Energy Agency
Io	Internet of Things
IOTA	Internet of Things Application
LCOE	levelized cost of electricit
LE	Local electricity market
M2	Machine to Machine
P2P	Peer to Peer
PBFT	Practical Byzantine Fault Tolerance
PoAu	Proof of Authority
Po	Proof of Stake
Po	Proof of Work
PP	Power Purchase Agreement
PV	Photovoltaic
RECs	Renewable Energy Certificate
RESs	Renewable Energy Sources
TS	Transmission System Operator
UK	United Kingdom
US	United States of America
V2	Vehicle to Vehicle
VP	Virtual Power Plan
ZF	Zero Footprint

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