IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received May 15, 2019, accepted May 30, 2019, date of publication June 4, 2019, date of current version July 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2920682

Blockchain Applications in Smart Grid–Review and Frameworks

AHMED S. MUSLEH[1], (Member, IEEE), GANG YAO[2], (Member, IEEE), AND S. M. MUYEEN[3], (Senior Member, IEEE)

[1]School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia
[2]Sino-Dutch Mechatronics Engineering Department, Shanghai Maritime University, Shanghai 201306, China
[3]School of Electrical Engineering Computing and Mathematical Sciences, Curtin University, Perth, WA 6102, Australia

Corresponding author: S. M. Muyeen (s.m.muyeen@ieee.org)

This work was supported by the National Natural Science Foundation of China under Grant 61673260 and Grant 61603246.

ABSTRACT Modern power systems face different challenges such as the ever-increasing electrical energy demand, the massive growth of renewable energy with distributed generations, the large-scale Internet of Things (IoT) devices adaptation, the emerging cyber-physical security threats, and the main goal of maintaining the system's stability and reliability. These challenges pose extreme pressure on finding advanced technologies and sustainable solutions for secure and reliable operations of the power system. The blockchain is one of the recent technologies that have gained lots of attention in different applications including smart grid for its uniqueness and decentralized nature. In the last few years, this technology grew a momentum specifically with the cryptocurrencies' industry such as the Bitcoin and Etherium. The Blockchain's applications in the smart grids could offer many innovative and affordable solutions to some of the challenges that the future and the current smart grids will be facing. This paper reviews different prospects, advantages, approaches, and technical challenges of utilizing the blockchain technology in the smart grid, and presents frameworks for key smart grid blockchain-based applications; more specifically, it is shown that how the blockchain can be used as the smart grid's cyber-physical layer.

INDEX TERMS Blockchain applications, cyber-physical security, energy trading, electric vehicles, micro-grid monitoring and control, smart grids.

I. INTRODUCTION

Today, energy demand is ever growing, and the need for electricity as an energy source is growing even faster [1]. Due to societal and technical developments, it will be inevitable that power generation from renewable energy sources will play a more vital role to fulfill the energy demand. Of all renewable energy sources, solar and wind energy will contribute to a large share in current and future generations. Compared to traditional power generation schemes, these distributed energy sources have specific characteristics which present new challenges to the current distribution system [2]. The main challenge is the appearance of the new type of grid user called the prosumer, who produces and consumes electrical energy in a local area [3]. The additional challenge is the intermittent nature of renewable energy sources such as solar and wind energy. The principal task of the electricity grid is to transmit energy in a stable manner [4]. Smart grids propose a solution to the integration of these distributed energy sources to maintain the security of supply of the electricity grid. The focus of smart grids is to facilitate local production and consumption by prosumers and consumers [3]. By stimulating local energy production and consumption, the transmission losses are reduced. Prosumers and consumers should be able to trade electricity with each other in a peer to peer fashion. To manage these transactions between consumers and prosumers participating within the smart grid in a centralized manner would likely to be very costly and would require complex communication infrastructure [5]. As a result, it would be clear that a decentralized method would be preferred [6]. Applications based on blockchain could offer solutions to problems of different levels of complexity within the smart grid.

Unlike many similar technologies, blockchain took a breakneck pace in the development and the utilization in many sectors of today's industry. A brief timeline of the

The associate editor coordinating the review of this manuscript and approving it for publication was Mouloud Denai.

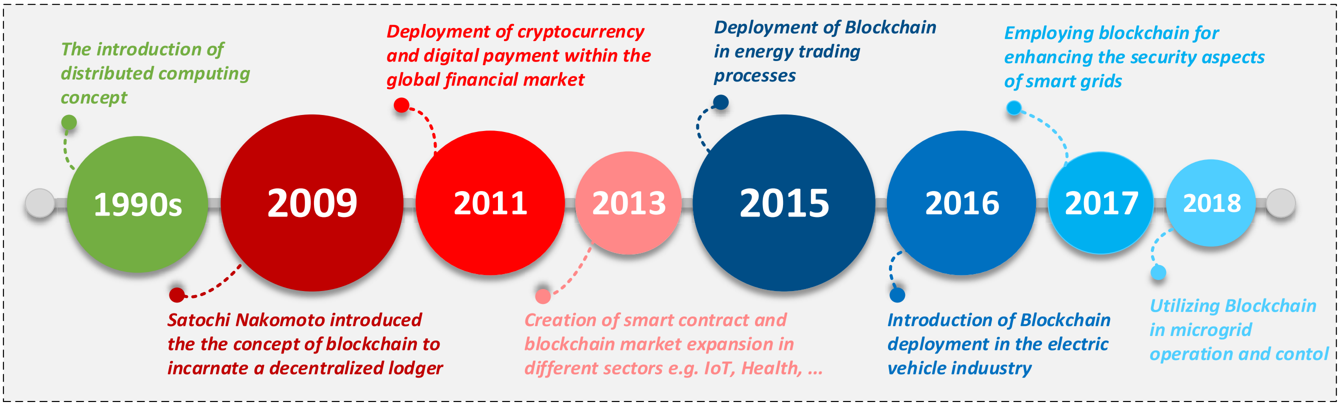

FIGURE 1. Blockchain development and utilization timeline with power system concertation.

emergence and utilization of blockchain technology is illustrated in Figure 1. Many researchers believe that Blockchain is a result of the introduction of the distributed computing concept that was introduced in the 1990s. Based on the concept, Satoshi Nakamoto introduced the concept in the blockchain technology for the first time in 2009 with his white paper "Bitcoin: A Peer-to-Peer Electronic Cash System" [7]. This white paper is considered as the mathematical foundation of the well-known Bitcoin cryptocurrency. Even though this paper laid out the basis for the Blockchain technology, the author's identity is unknown, and it was never actually submitted to any peer-reviewed journal. After the adoption of blockchain in cryptocurrency such as Bitcoin in 2011, the real applications of blockchain started with the introduction of smart contracts and the smart applications in 2013 [8]. Smart blockchain based contracts created a significant impact on the various industrial sectors such as markets, health, and the internet of things (IoT). Following this vast expansion of blockchain applications, the energy sector started the blockchain utilization with energy trading applications in 2015, electric vehicle applications in 2016, grid security applications in 2017, and even with the microgrid operation and control applications in 2018.

As a primary application in the smart grid, the application of Blockchain could offer a solution to establish a trading infrastructure within the smart grid [9]. Ideally, the application of the Blockchain would enable parties, in this case, consumers and prosumers within the smart grid, to trade electricity with each other in a peer to peer fashion without the intervention of a third party to ensure trust. The application of a blockchain based trading infrastructure within the smart grid promises a range of benefits [10], [11]. For example, one could think of advantages such as the establishment of a real-time market, less transaction cost due to a simplified trading structure and more privacy for users within the smart grid [12]. Besides utilizing the blockchain for realizing a trading infrastructure, more sophisticated and complex applications could be established by adding computational functionality. As a result, a decentralized computing platform can be created which could be used to offer a variety of solutions within smart grids [13]. For example, control within the smart grid could be enforced by variable pricing. Blockchain's potentials in the smart grids have just begun to be appreciated as noted via the growing number of studies and research projects. In 2016, the German Energy Agency published a survey on the views of energy decision-makers around the globe. The survey indicated that nearly 20% of the decision-makers believe that the blockchain technology will be a primary technology in the smart grids [14]. Future predictions of the blockchain technology's applications in the smart grids are briefly discussed in [15]–[18].

The main contribution of this paper is to explore, identify, summarize the applications including advantages and the technical challenges and framework development of the blockchain technology in smart grids. Our paper aims to narrow the gap of the different applications of the blockchain technology in the smart grids through the following points:

- We first provide a detailed and brief introduction of the blockchain technology starting with the main concepts and terminologies of the technology and ending with the main applications in outside the smart grids area. We also discuss some recent real-life applications.
- We then have an in-depth review and analysis of the blockchain's applications in smart grids in the various areas. Also, we detail the different validation approaches carried out by the different applications.
- We also provide some recent industrial applications of blockchain technology in the smart grids and proposed roadmap for future developments.

The rest of the paper is structured as the following: Section 2 introduces the blockchain technology from a wide perspective with some recent real-life applications, section 3 discusses the different applications of blockchain in smart, section 4 introduces new frameworks of blockchain in smart grid applications, a summary of the recent research testbeds and industrial utilization of blockchain in smart grid is presented in section 5, and the concluding remarks are illustrated in section 6.

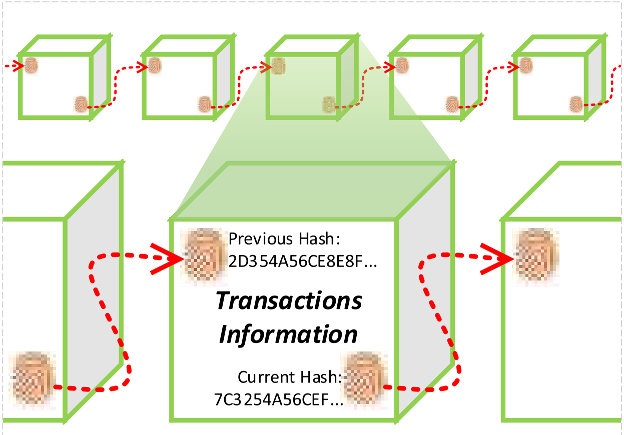

FIGURE 2. General blockchain structure.

II. BLOCKCHAIN TECHNOLOGY

The simplest definition of the blockchain is a chain that is constructed from many blocks that contain information [7]. The primary attribute of this technology is that it keeps track of all the variations in the blocks that it creates so that no block could be removed or modified. This results in making the blockchain technology a very secure method for transferring properties, money, and contracts without the need for a third-party intermediary agent like governments or banks [19]. In other words, the data that is contained in the blockchain cannot be changed once recorded. In terms of categorizing, the blockchain is basically a software protocol that cannot operate without the Internet. Blockchain based systems are composed of many pieces such as software applications, a database, and many connected computers known as lodgers. Even though the blockchain could be built via different programming language, Solidity, which is a high-level object-oriented programming language, is the primary programming language for many blockchain developers nowadays [20].

A. CONCEPTS, TERMINOLOGY, AND TYPES

As explained earlier, blockchain is a chain consisting of blocks containing information. Figure 2 illustrates a simple general structure of the blockchain.

In every blockchain, the first block is known as the Genesis block which is the foundation of the chain. Every newly created block is then connected with the preceding blocks in the chain; thus, every block is connected eventually to the genesis block. Aside from the information contained in each block, a hash is also present. The hash could be seen as a fingerprint that uniquely identifies each block and its contents as shown in Figure 2. Thus, any change in the block's content will result in a change in the associated hash [21]. Hashes provide a vital role in the blockchain operation as it acts as a main guarantee for blockchain security. Every block of the chain includes its own hash and the precious's one as illustrated in Figure 2. This technique makes the blockchain technology one of the most secure options in the industry nowadays [22]. In the case where a block is attacked by changing its information, the hash of the block itself will change; however, the hash in the next block will not. This results in indicating all the following blocks as an invalid block. Therefore, a change in the single block in the blockchain results in invalidating all the following blocks in the chain [22].

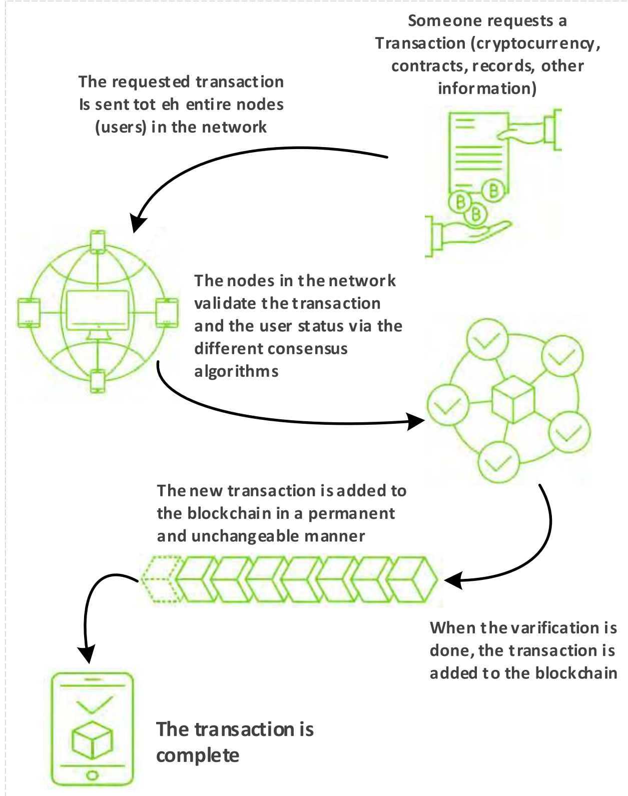

FIGURE 3. Blockchains transactions steps.

Blockchain operates via a generalized process that is illustrated in Figure 3. The process starts with a transaction request that could be initiated by any user. Then the transaction is broadcasted to all the users in the network. Following that, the verification process takes place where all of the nodes verify the transactions via the hashes. Once the verification is completed, the transaction is contained within a new block that is connected to the previous blockchain which makes it permeant and unchangeable [7]. The use of hashes provides an effective method in securing the blockchain. However, with the help of the super-fast computers, hackers could change the information in a single block and then recalculates all the hashes of the following blocks in the chain in a few minutes. To overcome this issue, several algorithms have been created to have what is known as the consensus [23]. The process of the consensus includes the verification of the transactions before that are added to the blockchains. This allows the blockchain to grow without the fear of the manipulating of the blocks or the information within them.

The consensus process takes place in predefined discrete time intervals. These intervals represent the times from the initiation of the transactions to the time of its addition to the blockchain. The confirmation time depends on the block size, transaction volumes, and the consensus algorithms utilized. Consensus algorithms with variable properties have been developed and utilized in the industry nowadays. The four well-known consensus algorithms are [24]:

- Proof of Work (PoW): this consensus algorithm is the most well-known and widely used algorithm within the various blockchain applications. With PoW, miners decide on the addition of the new blocks. Bitcoin and Ethereum are the two most popular utilizers of PoW consensus algorithm [25].
- Proof of Stake (PoS): in this consensus algorithm, no miners are present. Instead, the validation process is done via the validators based on their stake in the block creation. Thus, anyone who owns a good in the transaction could be a validator of the transactions. Unlike PoW, this algorithm plays a significant role in reducing the energy and time consumed in the consensus process. Nevertheless, PoS is still not sufficiently mature to be practiced in the industry like the PoW [25].
- Proof of Authority (PoA): with this algorithm, only approved accounts and users can place new transactions in the blocks. Thus, this approach could be seen as a more centralized pattern, which provides a faster consensus process [25].
- Practical Byzantine Fault Tolerance (PBFT): in this approach, a primary and a secondary replica are utilized in the consensus process. The secondary is continuously evaluating the primary decisions in the blockchains and make any necessary actions if the primary is compromised [25].

Aside from the consensus algorithms, blockchains can differ from in their "permission models," which is the types of permissions that are given to network users. Three main types of blockchains are noticed: public, private, Consortium:

- Public: The public blockchain is open to all of the users. Anyone can join and add to the blockchain as he likes. Thus, he can create new blocks as he wants.
- Private: in this type, only a few users can verify and add to the blockchain. Nevertheless, everyone on the network can view the status of the blockchain.
- Consortium: in here, a single group of the can be allowed to view, verify or add to the blockchain. Thus, it is controlled by authorized nodes only.

B. DISTINCT FEATURE OF BLOCKCHAIN DISTRIBUTED ARCHITECTURE

Blockchain has several attributes that make it different from different similar technologies. These distinctions could be summarized in the following points [7]:

- Decentralized: There is no need for central management to handle the transactions of the blockchain.
- Resilience: the decentralization of the blockchain makes it resilient to any possible attacks.

TABLE 1. Blockchain technology vs shared database.

Parameters	Blockchain	Shared Database
Operations allowed	Insert new blocks	Create/ Read/ Update and Delete
Replication	Full replication on every peer	Master-slave, Multi-master
Consensus	The peers agree on the transactions' outcome	Distributed transactions held separately.
Validation	Global rules govern the whole system	Offers only local integrity constraints
Disintermediation	It is allowed with blockchain.	Not allowed.
Confidentiality	Fully confidential	Not totally confidential
Robustness	Fully robust technology	Not entirely robust

- Time reduction: The quick transactions handled by the blockchain without the need for an intermediary makes it one of the fastest technology available nowadays
- Reliability: This is assured through the detailed and unchangeable history recoded in the blockchain.
- Fraud prevention: This is guaranteed with the shared information and consensus process that is agreed within all the blockchain users.
- Security: With the distributed architecture, attacking the blockchain is not a possible scenario unless all
- Transparency: All the changes and the transactions are shared with all the blockchain users.

The blockchain is usually compared to the shared database technologies where the information of the network is stored in a master data center that is accessible by the whole nodes of the network. The main differences of the different technologies could be summarized in Table 1.

C. MAJOR BLOCKCHAIN APPLICATION IN INDUSTRIES (NON-POWER)

The technology of Blockchain is used broadly in the different sectors such as Markets, Internet of Things (IoT), health and science. Most of these applications are still considered immature enough to be adopted by the industry except for the cryptocurrencies industry. Several Blockchain applications are summarized in Table 2.

D. REAL-LIFE BLOCKCHAIN UTILIZATION CASES

1) BITCOIN CRYPTOCURRENCY

In 2008, Satoshi Nakamoto launched the Bitcoin which is a sort of cryptocurrencies that is not governed by any government or bank. All the transactions made within the bitcoin industry are made publicly where anyone can view, verify, and participate in it. It is now considered to be the most popular cryptocurrency in the world. This cryptocurrency is made possible via the blockchain technology. Other similar cryptocurrencies include Ethereum, Ripple, and Litecoin [40].

TABLE 2. Main blockchain applications.

Sector	Usage
Markets	▪ Quota management in the Supply Chain Network [26] ▪ Billing, monitoring and Data Transfer [27] ▪ Monitoring of quality line [28]
Government Sector	▪ Registry & Identify [29] ▪ Digitization of contracts/documents and proof of ownership for transfers [30]
Internet of things (IoT)	▪ Integrated smart city [31] ▪ Smart home networks [32] ▪ Smart home sensors [33]
Health	▪ Data management [34] ▪ Healthcare records management [35] ▪ Digital health wallet Smart property [36]
Science & Art	▪ Crowd analysis [37] ▪ P2P resources [38]
Finance & Accounting	▪ Decartelized Capital markets using a network of the computer on the Blockchain [11] ▪ Digital Currency Payment [7] ▪ Accounting [39]

2) DUBAI: THE BLOCKCHAIN STRATEGY

In 2016, the government of Dubai introduced the blockchain strategy. The Dubai Blockchain Strategy establishes a roadmap for the Blockchain technology's introduction for Dubai and the creation of an open platform to share technology with countries across the world. The Dubai Blockchain strategy is built on three basics: government efficiency, international leadership, and industry creation [41].

3) HUMANITARIAN AID UTILIZATION OF BLOCKCHAIN

In 2017 the united nations (UN) world food program initiated a project known as humanitarian aid. It was introduced in the rural areas of Pakistan. Via the Blockchain, the beneficiaries received food, fund and all type of transactions are registered within a blockchain to assure the transparency and the security of the process [42].

III. BLOCKCHAIN APPLICATIONS IN SMART GRID

Many researchers and industry leaders believe that the rise of the blockchain technology will theoretically adopt advanced development and smooth the shift towards the smart grid. Decentralized technologies have always been a basis for many smart grid technologies [43]. The integration of renewable energy sources, energy storage devices, and electric vehicles into the electrical grid has begun a broad research area on new control schemes to address these issues [44]. The different and desirable advantages of blockchain technology created considerable interest in exploring and adopting this technology in smart grids [15]. Blockchains applications in the smart grid could be divided through the different parts of the smart grid as follows [45]:

- Power generation: Blockchain technology gives the dispatching agencies a full knowledge about the overall operation status of a power grid in a real-time perspective. This enables them to develop dispatching plans that would maximize profits.
- Power Transmission and Distribution: Blockchain systems enables the automation and control centers to have decentralized systems that overcome the main challenges seen in the traditional centralized systems.
- Power Consumptions: Similar to the generation and transmission sides, blockchain could be beneficial in this side by managing the energy trading between the prosumers and the different energy storage systems as well as the electric vehicles.

The following are the main categories where the blockchain applications are extensively studied and utilized in smart grids.

A. BLOCKCHAIN APPLICATIONS IN ENERGY TRADING

With the increase of microgrid and distributed generation, energy trading becomes a very hot topic for various researchers and industry leaders [46]. Blockchain played a very significant role in this area. The technology of blockchain was used to eradicate fraudulent behaviors as shown in [47]. The authors here proposed a blockchain based energy trading scheme that is secured and reliable to encourage long-term investments. In [48], a proof of origin certificate is issued to provide a guarantee of the trading process in the energy market. This adoption of blockchain in the trading process in the energy market helps in reducing the time and effort required by removing the intermediaries from the market. Thus, with blockchain, Peer to Peer (P2P) energy trading becomes a very promising future process. In P2P trading systems, the blocks inside the chain record the units of the generated electrical energy which allows the owners and buyers to have the deals instantly and independently. This gives the users (owners and buyer) the freedom of preferences, choices, and prices instead of relying on an intermediate agent [49]. Kounelis *et al.* [50], Hahn *et al.* [51], demonstrate that the intermediary-free blockchain-based electrical energy trading is beneficial and is possible and beneficial to the buyers and owners alike. Optimization of energy resources in P2P trading has been introduced in [52], where the authors the optimal power flow model is stored in the blockchain. In [53], a platform is introduced that focuses on the anonymity and the privacy of the users. The advantage if this platform it that it provides the users the freedom to directly negotiate the process. Luo *et al.* [54], blended the concept of blockchain with the Multi-Agent to form a two-layer based electricity trading system the first layer is based on Multi-agent system where the prosumers can negotiate the pricing issues. The second layer is the blockchain based layer which provides a secure and trusted platform to settle the transactions. In [55], a very interesting laboratory-scale implementation is presented. This implementation relays on a blockchain platform for the sake of exchanging solar energy.

B. BLOCKCHAIN APPLICATIONS IN ELECTRIC VEHICLES

Electric vehicles connection to the smart grids has been a very hot topic in the last few years as illustrated in [56]. The charging of the EVs is the primary concern when it comes to the connection with the smart grid as uncoordinated charging of these vehicles can put severe stress on the power grid [57]. Thus, several approaches are proposed to address this problem including the blockchain technology. Liu *et al.* [58], Su *et al.* [59] proposed an adaptive EV integration scheme that is based on the blockchain technology. Using this scheme, EVs integration becomes smothers in terms of reducing power fluctuations and charging costs. Researchers in [60] advised integrating the EVs with the blockchain technology to enable the EVs to use the blockchain to discover a near charging station that would bid for the chance of the EVs charging. The integration of blockchain in the EV charging process ensures the best location and price for the EV users while assuring the security and the privacy of the whole system as well [61].

C. BLOCKCHAIN APPLICATIONS IN MICROGRID OPERATIONS

Control of microgrid is becoming an important topic especially with the integration of the many distributed energy resources (DERs). The need for a demand-based control and optimized operation of the microgrid is the focus for the researchers nowadays [62]. Similarly, blockchain technology has been incorporated within this area for its possible advantages and profits. In [63], a DERs scheduling mechanism is designed based on the blockchain technology. The utilization of blockchain here provides a trustworthy platform so that all DERs are trusted and secured. Though blockchains are getting substantial interest as a platform for distributed computation and data supervision, Münsing *et al.* [52] examine their utilization to simplify the distributed optimization and control of DERs in microgrids where decentralized optimal power flow (OPF) model for scheduling a mix of DERs is proposed. Demand side management based on blockchain technology is investigated in [64]. The proposed scheme here can reduce the Peak-to-Average ratio to benefit the electrical grid as well as smoothing the dips in the load profile caused by constraints of the supply. A new perspective is presented in [18] where decentralization of medium-voltage direct-current (MVDC) link control is implemented via Blockchain. This control strategy gives the grid operators shared responsibilities within the energy system.

D. BLOCKCHAIN APPLICATIONS IN CYBER-PHYSICAL SECURITY

The introduction of smart grid created many vulnerabilities where many parts of the cyber-physical smart grid can be manipulated or attacked. The impacts of these attacks are deeply investigated in [65], where it can be concluded that cyber and physical attacks are deeply connected and shall be addressed as one entity. Gupta *et al.* [66] further detail the different aspects and background of the different cyber-physical security issues in the smart grid. Cyber-physical attacks vary in their type, form, and impact, such as 1) time synchronization attacks [67], 2) GPS spoofing attacks [68], and 3) Denial-of-Service (DOS) attacks [69]. A very important cyber-physical systems attack is the FDI attack where the attacker manipulates or injects false data either in the measurements or the control signals to alter the dynamics of the power grid [70]. This type of attacks could be very hazardous to the operation of the power grid as they are challenging to detect. Countermeasures against FDI attacks are classified in literature into protection-based schemes and detection-based schemes. Protection-based schemes basically rely on protecting the measurements of the power grid from being manipulated by increasing the redundancy of the power grid measurements [71]. The main drawbacks of the protection-based schemes are the unguaranteed effectiveness with the different operating conditions of the power grid and the extreme need for the measurement's redundancy [72]. Detection-based schemes utilize the Bayesian framework in detecting FDI attacks that would look like an anomaly among the set of measurements [73]. The main drawback of these schemes is the incapability of detecting FDI attacks that closely imitate the normal distribution of the measurements of the power grid which are also known as stealthy attacks [72]. Thus, several blockchain approaches have been investigated widely for increasing the grid immunity toward cyber-physical attacks. A general discussion on the different blockchain protection mechanisms is presented in [74]. Reference [75] presents an inclusive conversation on the blockchain technology adoption in enhancing the security, privacy, and robustness of the power grid, via utilizing the meters as nodes in a distributed network which encapsulates the meter's measurements as blocks in the chain. A blockchain based platform is utilized in [76], the user can monitor how the electricity is used without the fear of any manipulation from either party. In [77], smart contracts are utilized to improve smart grid cyber resiliency and secure transactive energy applications. This is extremely beneficial for energy trading applications as well. Kim [78] investigated the important perspective of utilizing blockchain technology in creating a trusted network for the operation of intelligent electric vehicles. Through his scheme, several cyber-attacks could be dealt with before severe consequences. From the different studies conducted in this area, it is noticed that the many distinct features of blockchain discussed in section 2.B are the basics for utilizing blockchain technology in protecting the smart grid.

IV. NEW FRAMEWORKS OF BLOCKCHAIN IN SMART GRIDS

The utilization of the blockchain in smart grids could offer various advantages to our current and future electrical power system. Most of the advantages to the electrical power system which are specifically linked to the characteristics and the working principles of the blockchain arise from the

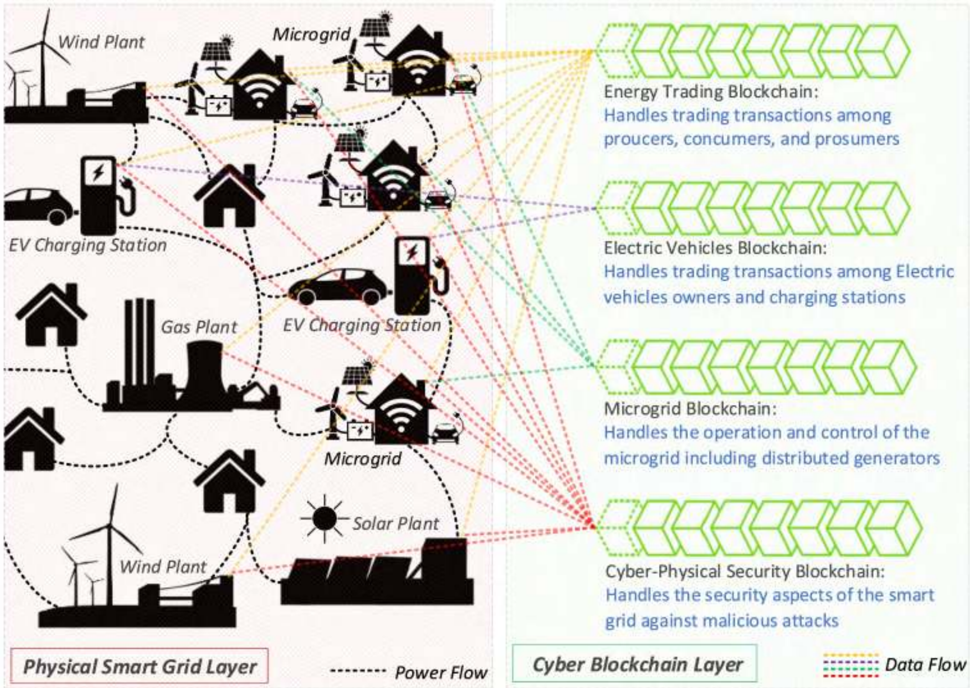

FIGURE 4. Blockchain as a new cyber layer of smart grids.

established decentralized trading infrastructure. The major advantages linked to characteristics and the working principles of the blockchain with respect to the electrical power system are the decentralization of trust, increased security, increased resilience, increased transparency, increased scalability, less bureaucracy, and increased computational capacity. From these advantages, several new frameworks of blockchain in smart grids could be adopted as illustrated next.

A. BLOCKCHAIN AS A CYBER LAYER

Blockchain could be easily integrated into the different parts of the smart grid by creating a cyber layer that is designed for the blockchain applications. Figure 4 illustrates how the blockchain technology could be a new cyber layer that supports the operation and the development of smart grids. It shows that every application in the smart grid could have its own specified blockchains such as energy trading and cyber-physical security blockchains. Energy trading blockchain shall be connected to the different energy traders in the grid such the power plants, consumers and prosumers. Electric vehicles blockchain facilitate the charging operations between the different stations and the prosumers. Microgrid blockchain handles the operations and the control of the microgrid with the various distributed generations in it. Finally, cyber-physical security blockchain shall be responsible for handling security and data protection issues in the smart grid. The integration of these different blockchains shall strengthen and smoothen the operation of the smart grid.

B. AGENT/AGGREGATOR BASED MICROGRID ARCHITECTURE

Through the adoption of an enhanced level of the blockchain, a decentralized computing platform is created in addition to the trading infrastructure. When all the peers who participate within the network devote a share of their computational capacity, the total available computational capacity is increased within the electrical power system. This is a critical aspect when it comes to the operation and control of the microgrids. Figure 5 illustrates a futuristic roadmap for the blockchain applications in microgrid operations. It illustrates that different components in the microgrids could have their own blockchains, such as smart metering aggregator, wind energy aggregator, and energy storage aggregator. These different chains shall provide the microgrids with a more flexible, reliable, and secure operation and control structure. Further, it increases the trust between the owners of these microgrids and the utilities as well. Moreover, the Blockchain increases the scalability of the electrical power system; hence if an extra customer would be connected to the microgrid there would be a negligible increase in complexity.

C. SMART GRID PROTECTION AND SECURITY

Blockchain offers increased security for the electrical power system. The applied cryptographic securitization combined with the consensus mechanism provides immutability of the data which has been incorporated in the Blockchain. Once an energy transaction/data has been included in the blockchain, it would be tough to alter this transaction for illegitimate

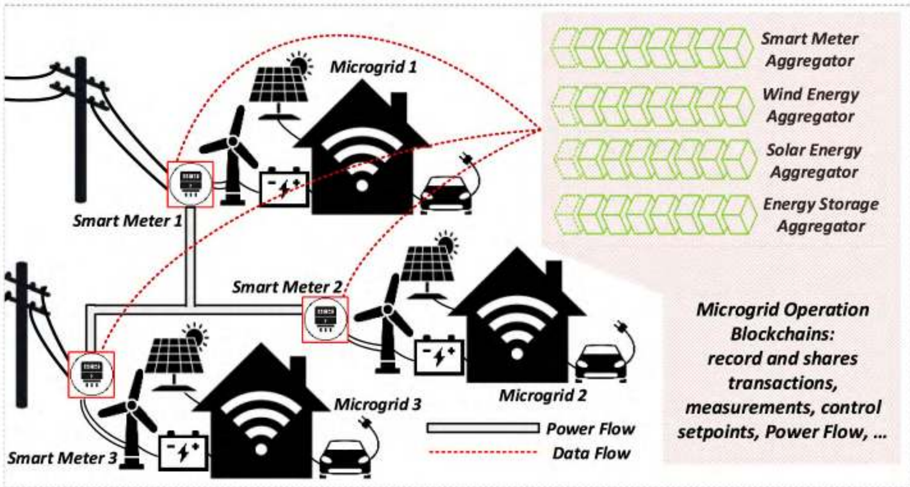

FIGURE 5. Microgrid automation based on blockchain technology.

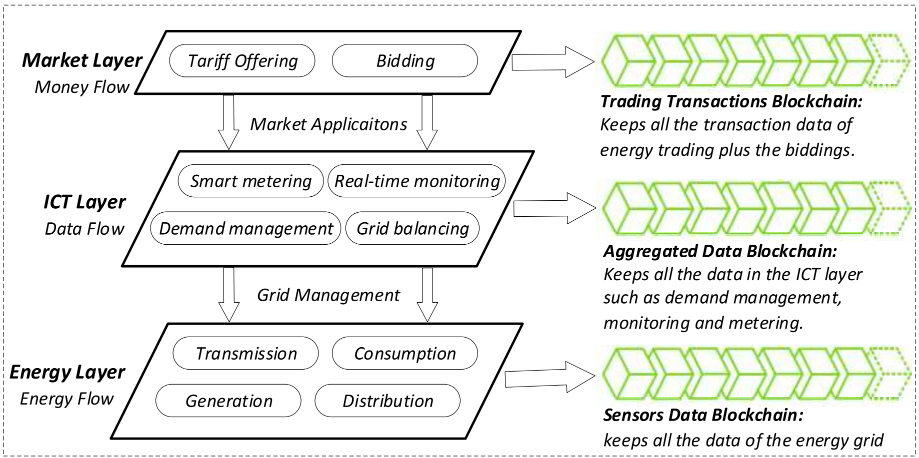

FIGURE 6. Blockchain applications framework in smart grid security and data protection.

purposes or to delete the transaction resulting in a very secure and robust system. The Blockchain also provides increased resiliency for the electrical power system. Since every peer in the network contains a copy of the ledger, there is an absence of a single point of failure compared to centralized data architectures which decrease the vulnerability for malicious attacks and therefore the electrical power system is more resilient. Besides, it increases the resilience of the electrical power system because the computational capacity is fragmented rather than concentrated in one giant computer. Figure 6 illustrates how different blockchains could be utilized in different smart grid layers for the sake of protecting the data. In this figure, every layer of the smart grid is handled by different blockchain aggregator. These blockchains shall have the protection means of the smart grid by providing a reliable and secure data storing platform. Furthermore, because there is no direct link between the identity within the Blockchain environment and the identity of the specific consumer/producer. Therefore, it will decrease the vulnerability against malicious attacks which increases the resilience of the electrical power system.

D. LIMITATIONS AND DRAWBACKS

Despite the marvelous attributes of blockchains, there are still many limitations that shall be considered in it such as:

- More expensive: nodes want greater rewards for accomplishing Transactions in a business which work with the code of demand and supply.
- Smaller ledger: this could affect the security and the immutability of the blockchain, and all the data stored in it.
- Slower transactions: transactions could be slower than usual process even with the absence of third-parties.
- Transaction expenses and speed of network: the transactions charge of the blockchain technology is rather high after being advertised as ‘nearly free’ during the first few years. Also, the computing capability and the

TABLE 3. Blockchain implementation approaches in smart grids.

Ref.	Validation approach
[47]	A trading process is designed, built and validated via ***Multichain*** [79].
[48]	An energy market is constructed via ***Corda*** and is coupled with an interface application that is developed with Predix platform [80].
[50]	Smart energy contracts implemented within ***Solidity*** platform [20].
[51]	A blockchain is built via ***Volttron*** platform, and it is coupled with smart city testbed developed in Washington State University [81].
[52]	A special ***Ethereum Homestead*** blockchain network is designed. Python/CVXpy is utilized to solve the desired optimization problems [82].
[54]	The system is simulated via Java Agent Development Environment ***JADE*** software [83].
[63]	The power system is simulated in MATLAB and the blockchain is realized with ***EthereumJS testrpc*** [84].
[64]	Several applications are associated, but the blockchain is developed with ***Zig-Ledger*** [85].
[18]	The blockchain is implemented here via ***TestRPC-Ethereum*** [86].
[55]	A laboratory implementation is utilized, and the blockchain is realized via ***Hyperlodger*** [87].

TABLE 4. Industrial blockchain utilization.

Corporation	Blockchain utilization
Energy Web Foundation [93]	This foundation is an alliance of major international energy leaders aiming at acceleration the blockchain technology in the energy market, this is a non-profit alliance that was founded in Argentina since 2017.
Electron [94]	This corporation is an energy supplier platform aiming at supporting P2P energy trading in UK since 2016.
Grid Singularity [95]	A corporation aiming at creating an open, decentralized energy data exchange platform internationally since 2016
Grid+ [92]	P2P electrical energy trading corporation with an aim of eliminating third-party intermediates in Texas, USA since 2017
Greeneum [96]	A decentralized Blockchain-based P2P market platform; it aims at redesigning the method that the renewable energy systems exchange the different needed data for their operations. It is expected to be released by 2019.
Drift [91]	P2P electrical energy trading corporation with an aim of eliminating third-party intermediates. It utilizes machine learning to provide better prices. It is based in New York, USA since 2014.
Bankymoon [97]	A blockchain development corporation which introduced prepaid blockchain-based smart meters in to support the electrical energy suppliers collect payments plus supporting humanitarian aid to be sent as energy via direct payments to the schools' smart meters in South Africa since 2015.
Power Ledger [98]	A corporation that is based on P2P energy trading as well as EV charging. It is based in Australia and New Zealand, since 2016.
SolarCoin Foundation [99]	The foundation t awards crypto coins to the registered and verified solar energy producers to foster solar energy generation. It is situated in more than 13 countries since 2014.
WePower [100]	A P2P renewable energy trading platform plus a fundraising corporation for renewables initiatives. It will be commenced in 2018 in Lithuania and Spain.
Sun Exchange [101]	P2P funding corporation to fund solar PV installations which will supply electrical energy to hospitals, schools, and similar businesses in South Africa since 2015.
Alliander [102]	A pilot smart P2P electrical energy market corporation. The energy tokens are also usable for services and goods within the society as well. It is based in The Netherlands, since 2017.
White Gum Valley energy sharing project [103]	A sharing power system that would enable neighbour to share their energy storage systems and the solar-powered microgrids. It is based in Australia.

response speed of blockchain technology cannot meet the requirements of the high-frequency transaction and dispatch of smart grids.

- Error risk: this risk is always present if the human factor is engaged even though the blockchain is a highly secured technology.
- Wasteful: each node in the blockchain must validate the transactions made and maintain the consensus across the blockchain. This is wasteful since every node repeats the task to reach the consensus agreed upon.

V. READINESS OF BLOCKCHAIN TECHNOLOGY IN SMART GRID

Blockchain applications in the smart grid are still considered to be immature in the sense that more studies, real experiments, and industrial utilizations are yet to be conducted and realized. The following subsections provide a brief overview of the recent testbeds and industrial utilization of blockchains.

A. BLOCKCHAIN TESTBED IMPLEMENTATIONS

Even though many authors suggested the utilization of blockchain in smart grid, very few demonstrated either a simulation or an experimental testbed for the proposed methodology. This indicates a great need for experimental research work to be conducted in this field which would further investigate the suitability of blockchain to real-world problems. Table 3 illustrates several research papers and their validation approaches toward blockchain adoption in the different smart grid applications.

B. RECENT INDUSTRIAL APPLICATIONS: (COMPANIES ADOPTION OF BLOCKCHAIN IN POWER INDUSTRY)

Even though the blockchain technology is a hot topic for the electrical energy researchers, the industry has started the main lead in adopting and developing blockchain technology as shown in Table 3. Several startups corporation, as well as established energy leaders, are tackling electrical energy sector problems via the blockchain technology. Table 4 (derived from [88]) represents a summary of the most protuberant electrical energy corporations that are currently leading in utilizing the blockchain technology. As illustrated in Table 4, there is a wide range of purposes and areas in the electrical energy sector where the blockchain technology is actively deployed. For instance, some corporations employ the blockchain technology for the P2P electrical energy trading with the aim of eliminating third-party intermediaries [89], [90]. Other corporations make use of the blockchain to be more affordable and competitive energy retail intermediaries [91], [92]. Other utilities employ the blockchain technology in different other objectives.

VI. CONCLUSION

Blockchain technology has gained considerable momentum mainly through the evolving industry of cryptocurrencies such as Bitcoin. The various and unique features of the blockchain technology has led many researchers and industries to invest broadly in it. Currently, the outlook on the blockchain as a technology is too optimistic, and the expectations of the value of the technology are too high, like the outlook and expectations of at the beginning of the internet. Like the different industrial sectors, power grids are starting a very impressive utilization of blockchain technology. This paper surveyed the recent applications and utilization of the blockchain in the smart grid sector from research and an industrial point of view. Furthermore, it illustrated the various advantages of the blockchain the electrical power system, as well as demonstrated a few new frameworks for the smart grid. However, to successfully implement the blockchain within the smart grid, significant challenges must be countered in the coming years.

REFERENCES

[1] S. M. Muyeen and S. Rahman, *Communication, Control and Security Challenges for the Smart Grid*. Edison, NJ, USA: IET, 2017.

[2] Y. Yolda , A. Önen, S. M. Muyeen, A. V. Vasilakos and . Alan, "Enhancing smart grid with microgrids: Challenges and opportunities," *Renew. Sustain. Energy Rev.*, vol. 72, pp. 205–214, May 2017.

[3] N. Gensollen, V. Gauthier, M. Becker, and M. Marot, "Stability and performance of coalitions of prosumers through diversification in the smart grid," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 963–970, Mar. 2018.

[4] K. Moslehi and R. Kumar, "A reliability perspective of the smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 1, pp. 57–64, Jun. 2010.

[5] T. Strasser, "A review of architectures and concepts for intelligence in future electric energy systems," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2424–2438, Apr. 2015.

[6] C.-H. Lo and N. Ansari, "Decentralized controls and communications for autonomous distribution networks in smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 66–77, Mar. 2013.

[7] S. Nakamoto. (2008). *Bitcoin: A Peer-to-Peer Electronic Cash System*. Accessed: Nov. 5, 2018. [Online]. Available: https://bitcoin.org/bitcoin.pdf

[8] T. Elysian. (2018). *The Global Emergence of Blockchain Technology*. Accessed: Jan. 25, 2019. [Online]. Available: https://medium.com/@Elysian_Ely/the-global-emergence-of-blockchain-technology-847fe9cdf2ee

[9] K. Tanaka, K. Nagakubo, and R. Abe, "Blockchain-based electricity trading with Digitalgrid router," in *Proc. IEEE Int. Conf. Consum. Electron.–Taiwan (ICCE-TW)*, Jun. 2017, pp. 201–202.

[10] M. Sabounchi and J. Wei, "Towards resilient networked microgrids: Blockchain-enabled peer-to-peer electricity trading mechanism," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integr. (EI2)*, Nov. 2017, pp. 1–5.

[11] K. Mannaro, A. Pinna, and M. Marchesi, "Crypto-trading: Blockchain-oriented energy market," in *Proc. AEIT Int. Annu. Conf.*, Sep. 2017, pp. 1–5.

[12] Z. Li, J. Kang, R. Yu, D. Ye, Q. Deng, and Y. Zhang, "Consortium blockchain for secure energy trading in industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 14, no. 8, pp. 3690–3700, Aug. 2018.

[13] M. Mylrea and S. N. G. Gourisetti, "Blockchain: A path to grid modernization and cyber resiliency," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2017, pp. 1–5.

[14] C. Burger, A. Kuhlmann, P. Richard, and J. Weinmann. (2016). *Blockchain in the Energy Transition. A Survey Among Decision-Makers in the German Energy Industry*. Accessed: Nov. 8, 2018. [Online]. Available: https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9165_Blockchain_in_der_Energiewende_englisch.pdf

[15] Z. Dong, F. Luo, and G. Liang, "Blockchain: A secure, decentralized, trusted cyber infrastructure solution for future energy systems," *J. Modern Power Syst. Clean Energy*, vol. 6, no. 5, pp. 958–967, Sep. 2018.

[16] T. Yang, Q. Guo, X. Tai, H. Sun, B. Zhang, W. Zhao, and C. Lin, "Applying blockchain technology to decentralized operation in future energy Internet," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integr. (EI2)*, Nov. 2017, pp. 1–5.

[17] M. Andoni, V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock, "Blockchain technology in the energy sector: A systematic review of challenges and opportunities," *Renew. Sustain Energy Rev.*, vol. 100, pp. 143–174, Feb. 2019.

[18] L. Thomas, Y. Zhou, C. Long, J. Wu, and N. Jenkins, "A general form of smart contract for decentralized energy systems management," *Nature Energy*, vol. 4, pp. 140–149, Jan. 2019.

[19] B. A. Tama, B. J. Kweka, Y. Park, and K.-H. Rhee, "A critical review of blockchain and its current applications," in *Proc. Int. Conf. Elect. Eng. Comput. Sci. (ICECOS)*, Aug. 2017, pp. 109–113.

[20] (2018). *Introduction to Smart Contracts—Solidity*. Accessed: Nov. 26, 2018. [Online]. Available: https://solidity.readthedocs.io/en/v0.5.3/index.html#

[21] R. Beck, "Beyond bitcoin: The rise of blockchain world," *Computer*, vol. 51, no. 2, pp. 54–58, Feb. 2018.

[22] G. Karame and S. Capkun, "Blockchain security and privacy," *IEEE Security Privacy*, vol. 16, no. 4, pp. 11–12, Jul. 2018.

[23] J. Moubarak, E. Filiol, and M. Chamoun, "On blockchain security and relevant attacks," in *Proc. IEEE Middle East North Africa Commun. Conf. (MENACOMM)*, Apr. 2018, pp. 1–6.

[24] M. N. Luke, S. J. Lee, Z. Pekarek, and A. Dimitrova. (2018). *Blockchain in Electricity: A Critical Review of Progress to Date*. Accessed: Nov. 10, 2018. [Online]. Available: http://www.energie-nachrichten.info/file/01%20Energie-Nachrichten%20News/2018-05/80503_Eurelectric_1_blockchain_eurelectric-h-DE808259.pdf

[25] D. Mingxiao, M. Xiaofeng, Z. Zhe, W. Xiangwei, and C. Qijun, "A review on consensus algorithm of blockchain," in *Proc. IEEE Int. Conf. Syst., Man, Cybern. (SMC)*, Oct. 2017, pp. 2567–2572.

[26] P. Brody. (Sep. 6, 2017). *How Blockchain is Revolutionizing the Supply Chain Management*. Accessed: Jan. 5, 2019. [Online]. Available: https://www.ey.com/Publication/vwLUAssets/ey-blockchain-and-the-supply-chain-three/$FILE/ey-blockchain-and-the-supply-chain-three.pdf

[27] N. Neidhardt, C. Köhler, and M. Nüttgens, "Cloud service billing and service level agreement monitoring based on blockchain," in *Proc. 9th Int. Workshop Enterprise Modeling Inf. Syst. Archit.*, 2018, pp. 1–5.

[28] Carrefour. (2019). *Carrefour is Now Using Blockchain Technology, Unlock-BC*. Accessed: Feb. 3, 2019. [Online]. Available: https://www.unlock-bc.com/news/2019-01-13/carrefour-is-now-using-blockchain-technology

[29] P. Bryzek. (2018). *How Blockchain is Used by Governments as a Form of National Identity*. Accessed: Jan. 10, 2019. [Online]. Available: https://medium.com/@bryzek/how-blockchain-is-used-by-governments-as-a-form-of-national-identity-e24a4eefb7d8

[30] A. Mizrahi. *A Blockchainbased Property Ownership Recording System*. Accessed: Jan. 10, 2019. [Online]. Available: https://chromaway.com/papers/A-blockchain-based-property-registry.pdf

[31] B. Algaze. (2018). A blockchain-based approach to smart cities. ExtremeTech. Accessed: Feb. 1, 2019. [Online]. Available: https://www.extremetech.com/extreme/265796-blockchain-approach-smart-cities

[32] C. Parashar. (2018). Blockchain: The future of smart home automation & security. Crypto Canucks. Accessed: Feb. 1, 2019. [Online]. Available: https://cryptocanucks.com/blockchain-the-future-of-smart-home-automation-security/

[33] A. Dorri, S. S. Kanhere, R. Jurdak, and P. Gauravaram, "Blockchain for IoT security and privacy: The case study of a smart home," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PerCom Workshops)*, Mar. 2017, pp. 618–623.

[34] Nick. (2018). Blockchain cases for healthcare. Industry review. Intellectsoft. Accessed: Feb. 2, 2019. [Online]. Available: https://blockchain.intellectsoft.net/blog/blockchain-cases-for-healthcare-industry-review/

[35] Y. Wehbe, M. A. Zaabi, and D. Svetinovic, "Blockchain AI framework for healthcare records management: Constrained goal model," in *Proc. 26th Telecommun. Forum (TELFOR)*, Nov. 2018, pp. 420–425.

[36] M. Patel, "Blockchain approach for smart health wallet," *Int. J. Adv. Res. Comput. Commun. Eng.*, vol. 6, no. 10, pp. 1–5, Oct. 2017.

[37] J. Wang, M. Li, Y. He, H. Li, K. Xiao, and C. Wang, "A blockchain based privacy-preserving incentive mechanism in crowdsensing applications," *IEEE Access*, vol. 6, pp. 17545–17556, 2018.

[38] Y. He, H. Li, X. Cheng, Y. Liu, C. Yang, and L. Sun, "A blockchain based truthful incentive mechanism for distributed P2P applications," *IEEE Access*, vol. 6, pp. 27324–27335, 2018.

[39] N. Andersen. (2016). *Blockchain Technology A Game-Changer in Accounting*. Accessed: Feb. 2, 2019. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/de/Documents/Innovation/Blockchain_A%20game-changer%20in%20accounting.pdf

[40] D. Vujičić, D. Jagodić, and S. Ranić, "Blockchain technology, bitcoin, and Ethereum: A brief overview," in *Proc. 17th Int. Symp. INFOTEH-JAHORINA (INFOTEH)*, Mar. 2018, pp. 1–6.

[41] (2016). *Dubai Blockchain Tehcnology*. Accessed: Feb. 1, 2019. [Online]. Available: https://www.smartdubai.ae/initiatives/blockchain

[42] T. Wetzel. (2018). *Humanitarian Aid: How Blockchain Technology Can Help Refugees and Those in Developing Countries, Medium*. Accessed: Jan. 5, 2019. [Online]. Available: https://medium.com/@twwetzel76/humanitarian-aid-how-blockchain-technology-can-help-refugees-and-those-in-developing-countries-2ebc9477b536

[43] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, Mar./Apr. 2009.

[44] H. Farhangi, "The path of the smart grid," *IEEE Power Energy Mag.*, vol. 8, no. 1, pp. 18–28, Jan./Feb. 2010.

[45] W. Su and A. Q. Huang, *The Energy Internet*. Sawston, U.K.: Woodhead Publishing, 2018.

[46] I. S. Bayram, M. Z. Shakir, M. Abdallah, and K. Qaraqe, "A survey on energy trading in smart grid," in *Proc. IEEE Global Conf. Signal Inf. Process. (GlobalSIP)*, Dec. 2014, pp. 258–262.

[47] K. N. Khaqqi, J. J. Sikorski, K. Hadinoto, and M. Kraft, "Incorporating seller/buyer reputation-based system in blockchain-enabled emission trading application," *Appl. Energy*, vol. 209, pp. 8–19, Jan. 2018.

[48] F. Imbault, M. Swiatek, R. de Beaufort, and R. Plana, "The green blockchain: Managing decentralized energy production and consumption," in *Proc. IEEE Int. Conf. Environ. Elect. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2017, pp. 1–5.

[49] B. Otjacques, P. Hitzelberger, S. Naumann and V. Wohlgemuth, *From Science to Society*. Springer, 2018.

[50] I. Kounelis, G. Steri, R. Giuliani, D. Geneiatakis, R. Neisse, and I. Nai-Fovino, "Fostering consumers' energy market through smart contracts," in *Proc. Int. Conf. Energy Sustainability Small Developing Econ. (ES2DE)*, Jul. 2017, pp. 1–6.

[51] A. Hahn, R. Singh, C.-C. Liu, and S. Chen, "Smart contract-based campus demonstration of decentralized transactive energy auctions," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Apr. 2017, pp. 1–5.

[52] E. Münsing, J. Mather, and S. Moura, "Blockchains for decentralized optimization of energy resources in microgrid networks," in *Proc. IEEE Conf. Control Technol. Appl. (CCTA)*, Aug. 2017, pp. 2164–2171.

[53] N. Z. Aitzhan and D. Svetinovic, "Security and privacy in decentralized energy trading through multi-signatures, blockchain and anonymous messaging streams," *IEEE Trans. Dependable Secure Comput.*, vol. 15, no. 5, pp. 840–852, Sep./Oct. 2018.

[54] F. Luo, Z. Y. Dong, G. Liang, J. Murata, and Z. Xu, "A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain," *IEEE Trans. Power Syst.*, to be published.

[55] M. Pipattanasomporn, M. Kuzlu, and S. Rahman, "A Blockchain-based platform for exchange of solar energy: Laboratory-scale implementation," in *Proc. IEEE Int. Conf. Green Energy Sustain. Develop. (ICUE)*, 2018, pp. 1–9.

[56] M. Yilmaz and P. T. Krein, "Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces," *IEEE Trans. Power Electron.*, vol. 28, no. 12, pp. 5673–5689, Dec. 2013.

[57] J. C. Mukherjee and A. Gupta, "A review of charge scheduling of electric vehicles in smart grid," *IEEE Syst. J.*, vol. 9, no. 4, pp. 1541–1553, Dec. 2015.

[58] C. Liu, K. K. Chai, X. Zhang, E. T. Lau, and Y. Chen, "Adaptive blockchain-based electric vehicle participation scheme in smart grid platform," *IEEE Access*, vol. 6, pp. 25657–25665, 2018.

[59] Z. Su, Y. Wang, Q. Xu, M. Fei, Y.-C. Tian, and N. Zhang, "A secure charging scheme for electric vehicles with smart communities in energy blockchain," *IEEE Internet Things J.*, to be published.

[60] J. Kang, R. Yu, X. Huang, S. Maharjan, Y. Zhang, and E. Hossain, "Enabling localized peer-to-peer electricity trading among plug-in hybrid electric vehicles using consortium blockchains," *IEEE Trans. Ind. Informat.*, vol. 13, no. 6, pp. 3154–3164, Dec. 2017.

[61] Y. Hou, Y. Chen, Y. Jiao, J. Zhao, H. Ouyang, P. Zhu, D. Wang, and Y. Liu, "A resolution of sharing private charging piles based on smart contract," in *Proc. 13th Int. Conf. Natural Comput., Fuzzy Syst. Knowl. Discovery (ICNC-FSKD)*, Jul. 2017, pp. 3004–3008.

[62] T. Samad and A. M. Annaswamy, "Controls for smart grids: Architectures and applications," *Proc. IEEE*, vol. 105, no. 11, pp. 2244–2261, Nov. 2017.

[63] P. Danzi, M. Angjelichinoski, Č. Stefanović, and P. Popovski, "Distributed proportional-fairness control in microgrids via blockchain smart contracts," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2017, pp. 45–51.

[64] S. Noor, W. Yang, M. Guo, K. H. van Dam, and X. Wang, "Energy demand side management within micro-grid networks enhanced by blockchain," *Appl. Energy*, vol. 228, pp. 1385–1398, Aug. 2018.

[65] Y. Mo, T. H.-J. Kim, K. Brancik, D. Dickinson, H. Lee, A. Perrig, and B. Sinopoli, "Cyber–physical security of a smart grid infrastructure," *Proc. IEEE*, vol. 100, no. 1, pp. 195–209, Jan. 2011.

[66] A. Gupta, A. Anpalagan, G. H. S. Carvalho, A. S. Khwaja, L. Guan, and I. Woungang, "Prevailing and emerging cyber threats and security practices in IoT-Enabled smart grids: A survey," *J. Netw. Comput. Appl.*, vol. 132, pp. 118–148, Apr. 2019.

[67] Z. Zhang, S. Gong, A. D. Dimitrovski, and H. Li, "Time synchronization attack in smart grid: Impact and analysis," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 87–98, Mar. 2013.

[68] C. Konstantinou, M. Sazos, A. S. Musleh, A. Keliris, A. Al-Durra, and M. Maniatakos, "GPS spoofing effect on phase angle monitoring and control in a real-time digital simulator-based hardware-in-the-loop environment," *IET Cyber-Phys. Syst., Theory Appl.*, vol. 2, no. 4, pp. 180–187, 2017.

[69] S. Liu, X. P. Liu, and A. El Saddik, "Denial-of-Service (dos) attacks on load frequency control in smart grids," in *Proc. IEEE PES Innov. Smart Grid Technol. Conf. (ISGT)*, Washington, DC, USA, Feb. 2013, pp. 1–6.

[70] G. Liang, J. Zhao, F. Luo, S. R. Weller, and Z. Y. Dong, "A review of false data injection attacks against modern power systems," *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1630–1638, Jul. 2017.

[71] Q. Yang, J. Yang, W. Yu, D. An, N. Zhang, and W. Zhao, "On false data-injection attacks against power system state estimation: Modeling and countermeasures," *IEEE Trans. Parallel Distrib. Syst.*, vol. 25, no. 3, pp. 717–729, Mar. 2014.

[72] G. Chaojun, P. Jirutitijaroen, and M. Motani, "Detecting false data injection attacks in AC state estimation," *IEEE Trans. Smart Grid*, vol. 6, no. 5, pp. 2476–2483, Sep. 2015.

[73] H. M. Khalid and J. C.-H. Peng, "A Bayesian algorithm to enhance the resilience of WAMS applications against cyber attacks," *IEEE Trans. Smart Grid*, vol. 7, no. 4, pp. 2026–2037, Jul. 2016.

[74] D. Minoli and B. Occhiogrosso, "Blockchain mechanisms for IoT security," *Internet Things*, vols. 1–2, pp. 1–13, Sep. 2018.

[75] G. Liang, S. R. Weller, F. Luo, J. Zhao, and Z. Y. Dong, "Distributed blockchain-based data protection framework for modern power systems against cyber attacks," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3162–3173, May 2019.

[76] J. Gao, K. O. Asamoah, E. B. Sifah, A. Smahi, Q. Xia, H. Xia, X. Zhang, and G. Dong, "GridMonitoring: Secured sovereign blockchain based monitoring on smart grid," *IEEE Access*, vol. 6, pp. 9917–9925, Mar. 2018.
[77] M. Mylrea and S. N. G. Gourisetti, "Blockchain for smart grid resilience: Exchanging distributed energy at speed, scale and security," in *Proc. Resilience Week (RWS)*, Sep. 2017, pp. 18–23.
[78] S. Kim, "Chapter two—Blockchain for a trust network among intelligent vehicles," *Adv. Comput.*, vol. 111, pp. 43–68, 2018.
[79] *Multichain: Open Platform for Building Blockchains*. Accessed: Feb. 18, 2019. [Online]. Available: https://www.multichain.com/
[80] *Welcome to Corda*. Accessed: Feb. 19, 2019. [Online]. Available: https://docs.corda.net/
[81] *Volttron*. Accessed: Feb. 19, 2019. [Online]. Available: https://volttron.org/
[82] *Ethereum Homestead Documentation*. Accessed: Feb. 20, 2019. [Online]. Available: http://www.ethdocs.org/en/latest/
[83] *JAVA Agent DEvelopment Framework*. Accessed: Feb. 21, 2019. [Online]. Available: http://jade.tilab.com/
[84] *Ethereumjs-testrpc-sc*. Accessed: Feb. 21, 2019. [Online]. Available: https://www.npmjs.com/package/ethereumjs-testrpc-sc
[85] *Z-Ledger*. Accessed: Feb. 21, 2019. [Online]. Available: https://baas.zhigui.com/index
[86] *Test RPC Configuration and Usage*. Accessed: Feb. 22, 2019. [Online]. Available: https://nethereum.readthedocs.io/en/latest/ethereum-and-clients/test-rpc/
[87] *Hyperledger*. Accessed: Feb. 22, 2019. [Online]. Available: https://www.hyperledger.org/
[88] J. Deign. (2017). 15 firms leading the way on energy blockchain. Greentech Media. Accessed: Feb. 1, 2019. [Online]. Available: https://www.greentechmedia.com/articles/read/leading-energy-blockchain-firms#gs.RmoOyai1
[89] A. Rutkin. (2016). Blockchain-based microgrid gives power to consumers in New York. New Scientist. Accessed: Feb. 2, 2019. [Online]. Available: https://www.newscientist.com/article/2079334-blockchain-based-microgrid-gives-power-to-consumers-in-new-york/
[90] LO3Energy. (2016). *Reshaping the Energy Future*. Accessed: Feb. 2, 2019. [Online]. Available: https://lo3energy.com/
[91] *Drift*. Accessed: Feb. 3, 2019. [Online]. Available: https://www.joindrift.com/
[92] (2019). *Grid+*. Accessed: Feb. 3, 2019. [Online]. Available: https://gridplus.io/
[93] *The Energy Web*. Accessed: Feb. 2, 2019. [Online]. Available: http://energyweb.org/
[94] *Electron*. Accessed: Jan. 30, 2019. [Online]. Available: http://www.electron.org.uk/
[95] *Grid Singularity*. Accessed: Jan. 30, 2019. [Online]. Available: http://gridsingularity.com/
[96] *Greeneum*. Accessed: Jan. 30, 2019. [Online]. Available: https://www.greeneum.net/
[97] *Bankymoon*. Accessed: Jan. 30, 2019. [Online]. Available: http://bankymoon.co.za/
[98] *Power Ledger*. Accessed: Jan. 29, 2019. [Online]. Available: https://www.powerledger.io/
[99] *Solar Coin*. Accessed: Jan. 29, 2019. [Online]. Available: https://solarcoin.org/
[100] *WePower*. Accessed: Jan. 29, 2019. [Online]. Available: https://wepower.network/
[101] *Sun Exchange*. Accessed: Jan. 29, 2019. [Online]. Available: https://thesunexchange.com/
[102] *Alliander*. Accessed: Jan. 30, 2019. [Online]. Available: https://www.alliander.com/en
[103] *White Gum Valley Energy Sharing*. Accessed: Feb. 23, 2019. [Online]. Available: https://westernpower.com.au/energy-solutions/projects-and-trials/white-gum-valley-energy-sharing/

AHMED S. MUSLEH (S'11–M'17) received the B.Sc. degree (Hons.) in electrical engineering from Abu Dhabi University, Abu Dhabi, United Arab Emirates, in 2014, and the M.Sc. degree in electrical engineering from Khalifa University, Abu Dhabi, in 2016. He is currently pursuing the Ph.D. degree with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, Australia. His research interests include smart grid technologies, wide area monitoring and control, cyber-physical security, machine learning, and Blockchain's applications. He received the Abu Dhabi University Overall Award of Excellence and the Petroleum Institute Graduate Fellowship, in 2014 and 2015, respectively.

GANG YAO (M'18) received the M.S. and Ph.D. degrees from the Electrical Engineering Department, Shanghai Maritime University, Shanghai, China, in 2003 and 2008, respectively. In 2008, he joined the Institut de Recherche en Communications et en Cybernétique de Nantes (IRCCyN), Nantes, France, as a Postdoctoral Research Fellow. Since 2009, he has been an Assistant Professor with the Electrical Engineering Department, Shanghai Maritime University. His current research interests include multi-agent based intelligent control, fault diagnosis, faults tolerant control of microgrids, and marine power systems.

S. M. MUYEEN (S'03–M'08–SM'12) received the B.Sc.Eng. degree from the Rajshahi University of Engineering & Technology (RUET), Bangladesh, in 2000, and the M.Eng. and Ph.D. degrees from the Kitami Institute of Technology, Japan, in 2005 and 2008, respectively, all in electrical and electronic engineering. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, Curtin University, Perth, Australia. He has published more than 200 articles in different journals and international conferences. He has authored or an editor published six books. His research interests include power system stability and control, electrical machine, FACTS, energy storage systems (ESS), renewable energy, and HVDC systems. He is the Fellow of Engineers Australia. He is serving as an Editor/Associate Editor for many prestigious Journals from IEEE, IET, and other publishers including, the IEEE Transactions of Sustainable Energy, the IEEE Power Engineering Letters, *IET Renewable Power Generation*, and *IET Generation, Transmission & Distribution*. He has been a Keynote Speaker and an Invited Speaker at many international conferences, workshops, and universities.