Bulletin of Electrical Engineering and Informatics
Vol. 14, No. 4, August 2025, pp. 2497~2513
ISSN: 2302-9285, DOI: 10.11591/eei.v14i4.8956

Blockchain for future smart grid: a comprehensive survey

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Article Info

Article history:

Received Jul 1, 2024
Revised Apr 9, 2025
Accepted May 27, 2025

Keywords:

Blockchain
Counterfeiting
Energy trading
Enhancing trust
Smart grid

ABSTRACT

Due to the unique features and characteristics of blockchain technology, its applications have expanded across various sectors, including finance, banking, supply chains, and smart grids (SGs). Blockchain ensures security and trust in transactions without requiring a third party, making it particularly valuable in decentralized systems. This paper explores the integration of blockchain technology into SG systems. It begins with a comprehensive review of conventional and smart power grids, identifying the key challenges modern SGs face, particularly issues related to trust and fraud. An in-depth analysis of blockchain technology follows, highlighting its potential, advantages, and defining characteristics. The study then examines several blockchain-based SG applications and provides a comparative analysis of prior research. The findings of this review illuminate the critical role of blockchain in enhancing SG performance by addressing trust and fraud prevention challenges. Furthermore, this research has significant implications for the energy sector, as it underscores the potential of blockchain to revolutionize SGs through increased security, transparency, and efficiency. By providing a foundation for future studies, this paper aims to guide the development of unified blockchain frameworks that address scalability, privacy, and energy management, paving the way for a more secure and efficient decentralized energy system.

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1. INTRODUCTION

Over the recent years, energy has been the nerve and essential element of this life, as since its inception it has witnessed a series of major and fundamental developments, starting from conventional power grids (CPGs) that are generated through central energy systems that rely on fossil fuels to generate energy, which causes variations and disparities in prices [1], up to smart grids (SGs) where the concept of what is known as the SG emerged in response to the challenges facing the CPGs, which in turn is based on improving the quality, efficiency and availability of energy while improving the use of renewable energy resources such as wind and solar energy. Unlike conventional systems which ensure the one-way flow of energy to consumers [2], the SG enables the exchange of energy in both directions between consumers and producing consumers-users who generate their own energy and can sell excess energy to the grid or other consumers [3].

According to [4], there are three levels to SG architecture. Firstly, the conventional infrastructure is used to transport electricity via lines and transformers. Secondly, a communication architecture is used to collect data from sensors installed on electrical networks. Lastly, it includes applications and services, in particular, remote troubleshooting systems and automatic demand response programs. Moreover, the SG system represents a modern electricity network that incorporates advanced communication, control, and monitoring technologies to optimize electricity generation, distribution, and consumption [5].

Despite the various advantages and features enjoyed by SG systems, such as facilitating the integration of renewable energy sources by enhancing the reliability, efficiency, and sustainability of the electricity sector, in addition to improving supply and demand management, and reducing the carbon footprint associated with energy production and consumption [6], SG systems face different challenges, including the lack of trust and transparency among stakeholders, vulnerability to cyberattacks and counterfeiting issues, and the complexity of integrating diverse technologies and systems.

To overcome the challenges faced by SG systems, especially in terms of enhancing trust and preventing counterfeiting problems, it is necessary to use one of the techniques or mechanisms that enhance trust and prevent counterfeiting issues. One of these mechanisms is called blockchain technology, which underlies cryptocurrencies like Bitcoin [7], this technology shows promise in enhancing trust and security within the SG system. Blockchain technology operates as a decentralized and distributed ledger, ensuring secure and transparent transaction records. Through cryptography and consensus algorithms, blockchain technology establishes an unalterable and auditable transaction history that all parties can verify [8]. Additionally, blockchain technology reduces the reliance on third parties (intermediaries), improving transaction efficiency and speed.

The main motivation for this study derives from the significant potential of blockchain technology to address various complexities within the SG, with a particular focus on enhancing reliability. Blockchain offers a wide exhibition of solutions spanning multiple layers of the SG infrastructure, providing trust, transparency, and security mechanisms. The objective of this research is to offer a thorough overview of SGs and investigate the crucial role that blockchain technology can have in managing them. This study delivers a detailed examination of blockchain-based applications, emphasizing their benefits, the technical strategies employed, and the challenges encountered when incorporating this technology into SG infrastructures.

This survey contributes to advancing SG systems by demonstrating how blockchain technology can enhance trust and prevent fraud within these networks. Unlike prior studies, it delves into the distinct benefits of blockchain, such as enabling secure energy trading and decentralized resource management. Through a review of relevant studies, the survey highlights blockchain's role in improving transparency and efficiency, reducing reliance on third-party intermediaries. The study further outlines future research directions, emphasizing the need for scalable solutions and integration with IoT and renewable energy systems.

The organization of the paper is as follows: section 2 presents the methodology of the paper, detailing a survey-based grounded in a comprehensive literature review to analyze blockchain integration into SG systems. Section 3 describes blockchain technology, covering its architecture, classification, transactions, consensus mechanisms, and smart contracts. Section 4 discusses the applications, proposed models, and projects leveraging blockchain technology in the SG sector. Section 5 presents the discussion of the paper. Finally, the conclusion and future work of the paper are presented in section 6.

2. METHOD

This research was based on a survey approach based on a comprehensive literature review on integrating blockchain technology into SG systems. Initially, the infrastructure of both conventional and SGs was assessed, highlighting key challenges in modern SGs, particularly related to trust and fraud. Subsequently, blockchain technology was examined in detail, focusing on its capabilities and advantages within SG applications. The research involved reviewing blockchain-based SG studies. Techniques of literature review and comparative evaluation were applied to analyze previous research. Literature was sourced from well-established academic platforms like IEEE and Elsevier. The selection emphasized studies that clearly demonstrated the use of blockchain to enhance SG performance. Additionally, a comparative analysis of blockchain applications in SGs was conducted, concentrating on their role in enhancing trust and reducing fraud. Descriptive and comparative analytical methods were employed to assess blockchain's effectiveness in SGs. Studies that lacked substantial evidence of blockchain's impact were excluded, while those presenting practical implementation examples were given priority. The findings are structured to aid future researchers in replicating and extending the research.

2.1. Conventional power grid and smart grid

A CPG, sometimes called an electrical grid, is a network of power plants, substations, transformers, and power lines that facilitates the connection between energy producers and consumers of that energy [9]. Traditionally, the CPG depends on the main procedures, particularly generation, transmission, distribution, and electricity control [10]. In CPG, electricity is generated centrally through one of the national electricity companies or some private electricity companies. These companies generate electricity using generators that mostly use fossil fuels, and then distribute it to consumers through transmission power lines. Therefore, generation and demand must be balanced because they are based on real-time [11]. This implies that electricity is generated, transmitted, and distributed instantly when a light switch is turned on. Unlike water and gas systems, electric power systems do not function as storage systems [11].

As shown in Figure 1, CPG consists of generation, transmission, distribution, and consumption. Power is typically generated at centralized plants, such as coal, gas, or nuclear power plants [12]. From there, it is transmitted over long distances using high-voltage transmission lines to reduce energy losses. Finally, it is distributed to end-users, including residential, commercial, and industrial consumers, through lower-voltage distribution lines [2].

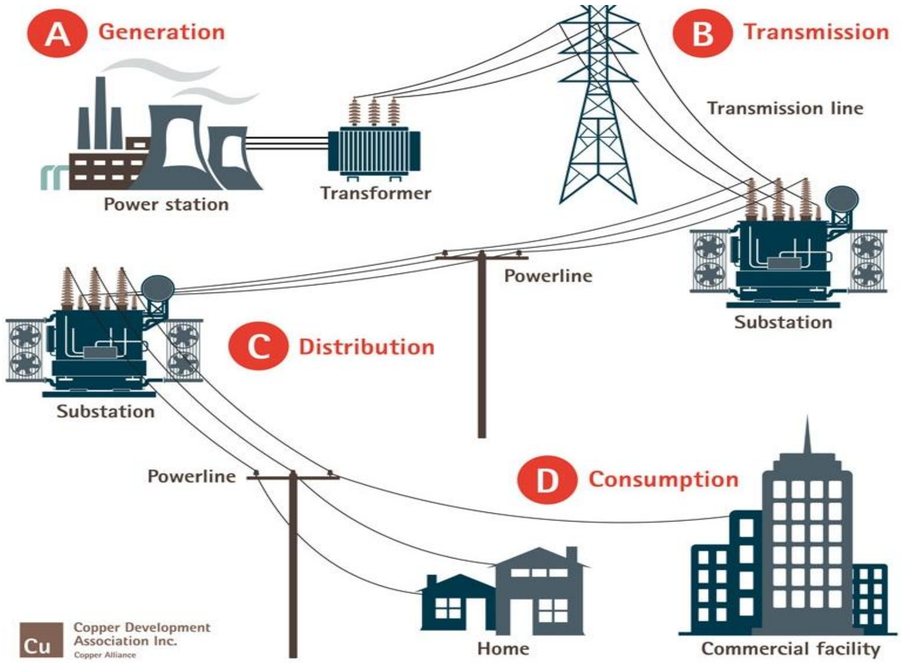

Figure 1. The flow of electricity from the moment of generation until it reaches the consumer [13]

CFG has played an important role in fulfilling the ever-increasing demand for electricity in modern society, as it has been designed to fulfill the needs of consumers in the 20th century [14]. Due to the traditional electricity network's reliance on fossil fuel-fueled centralized power generation, carbon emissions frequently give rise to several environmental challenges and concerns. Additionally, because of its central nature, it may be subject to interruptions from natural disasters or equipment failures, which could result in power outages and service failures. To overcome these challenges, the term SG has appeared [3].

Recently, due to the advantages of the SG, experts and researchers have been interested in studying the SG [15], as the scientific community has shown great research interest in SGs. So, the rapid developments in computer and communication technology made it possible to realize the concept of SG. Whereas a critical aspect of the SG is its transformative impact on energy distribution, the transition from a centralized energy system to a distributed energy system [16]. Accordingly, the SG as shown in Figure 2, is conceptualized as an electricity distribution system that utilizes advanced control mechanisms to efficiently deliver power from generation sources to consumers [17]. Consumers play a pivotal role in the SG as active participants who can adapt their purchasing patterns and behaviors based on the information, incentives, and disincentives they receive [18]. By incorporating consumer engagement, the SG aims to optimize electricity delivery and foster a more interactive and responsive energy ecosystem.

By studying both types, it becomes clear to us that each of them has certain characteristics on the one hand and faces certain challenges on the other hand, the advantages of the SG are the variety of energy generation sources in the SG, decentralization, and variety of infrastructure [20], while decentralization can make we have a state of mistrust and lack of transparency among customers, while the conventional grid is characterized by general stability due to the presence of a central authority that manages it, with limited infrastructure when compared to the SGs. Table 1 presents a comparison between the conventional and SGs in terms of several characteristics, while Table 2 presents the most important terms used in both grids.

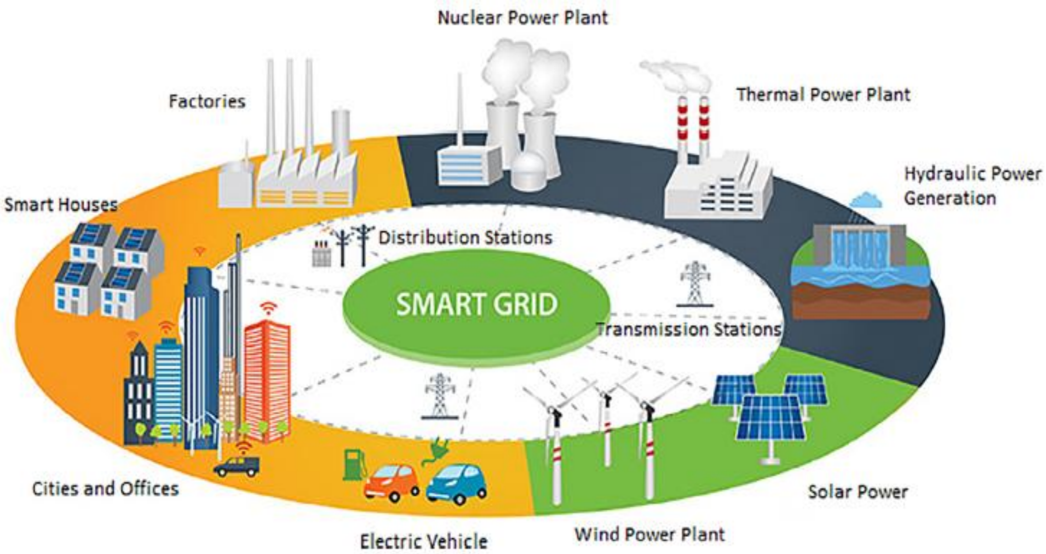

Figure 2. A diagram of SG [19]

Table 1. A brief comparison between the conventional grid and the SG

Characteristics	Ref.	Conventional grid	SG
Infrastructure		Limited	Various
Self-healing	[10]	Responds after an error occurs	Automatically detects and responds to problems
Power flow control	[16]	Limited	large-scale
Transaction	[18]	The transaction is one-way, consumers buy energy through energy companies	The transaction is done directly between prosumers and consumers (multi-direction)
Generation	[20]	Centralized	Decentralized
Communication	[21]	One-way	Two-way
Power source		Fossil fuel-based power plants	Solar, wave, geothermal, and other alternative energy sources can all be used to generate power
Cost		Expensive	Cheap
Participation		Do not participate	participate actively
Reaction time	[21]	Slow	Extremely quick

Table 2. The most important terms used in CPG and SG

Term	Description
Conventional grid	A traditional one-way electricity distribution system without advanced technologies or high communication capabilities.
SG	Unlike the conventional grid, the advanced electricity distribution system that incorporates communication, control, and information technologies to enhance efficiency, reliability, and sustainability.
Consumer	An individual or entity that uses electricity for personal or business purposes.
Producer	A company or entity that generates electricity, usually through power plants or renewable energy sources.
Prosumer	An individual or entity that both consumes and produces electricity, often through renewable energy sources.

3. BLOCKCHAIN TECHNOLOGY

In 2008, BC technology was proposed by Satoshi Nakamoto to support the first cryptocurrency which is Bitcoin [22]. However, BC is not confined to the field of cryptocurrency but can be used in various fields such as the financial sectors, health insurance, automatic transaction settlement, traceability, and the SG [18]. BC is a very safe and secure technology to transfer money, contracts, and sales operations in general, as it does not need a third-party intermediary agent such as banks and governments because the main feature of BC is to track all the blocks that are created so that they cannot be modified or deleted due to their distributed presence thus ensuring the correctness of the transactions [23]. The process starts when someone requests a transaction, then the requested transaction is broadcast to others over the network using peer-to-peer, in which each node stores data and forward it to all other nodes, that is, communication takes place between peers without the need for a central node [24]. Following that, the nodes validate the transactions and the user status using one of the well-known algorithms. Once the transaction is verified, it is combined with other transactions to create a new data block. After that, the new block is added to the existing blockchain to be permeant and unchangeable or modified [7].

3.1. Blockchain architecture

A blockchain consists of a sequence of blocks connected, the first block is called a genesis block (block 00), Figure 3 shows genesis block structure, later any block that is created is indicated by the block number n+1 (block 01 and block 02), and each newly created block is connected to the blocks that were created earlier [25]. In general, the blockchain consists of blocks and transactions, where the transactions refer to the actions done by the parties in the network, while the blocks record these transactions made by the parties and ensure that they have not been tampered with [26]. According to Figure 4, each block within a blockchain technology has two main components, block header and block body, where the header consists of metadata such as block number, nonce, previous hash, current hash, and timestamp, while the block body contains a list of all successful or valid transactions in the network [27].

Genesis Block	
Previous Hash	0
Timestamp	Thu, 27 Jul 2017 02:30:00 GMT
Data	Welcome to Blockchain CLI!
Hash	0000018035a828da0…
Nonce	56551

Figure 3. Genesis block str

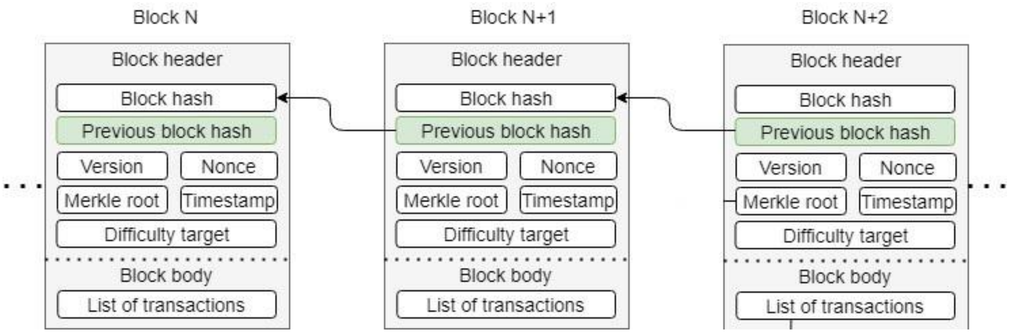

Figure 4. Structure of blockchain

Furthermore, each block is secured by the hash function, which is shown in Figure 5, simply, the hash function is a one-way mathematical function that produces a constant output, so that any slight change in the input will lead to a big change in the output [18]. Thus, the hash function is similar to the fingerprint function because it uniquely identifies each block and its contents, that means, any change in the hash function will invalidate all the following blocks, so it acts an essential role in blockchain technology because it performs the main guarantee for blockchain security [25]. Meanwhile, blockchain uses consensus mechanisms such as proof of work. In this case, blockchain works in a network of computers called "miners", which are very necessary and important in the blockchain if the proof of work mechanism is used [28].

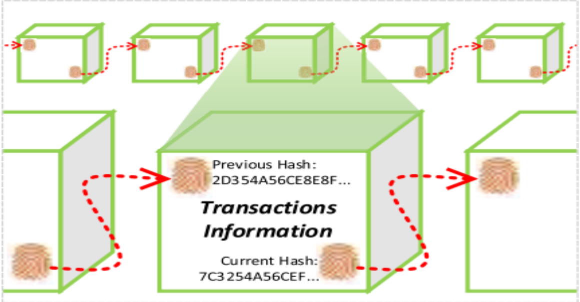

Figure 5. Hash in blockchain structure [25]

3.2. Classification of blockchain

Since the emergence of blockchain technology, many significant developments appear, especially in terms of classification. As this has led to advancements and improvements in blockchain technology, enabling it to fulfill new challenges and meet the growing demands of various sectors. Blockchain technology has several different classifications. It can be classified into three main classifications as public blockchain also referred to as open or permissionless, private blockchain also referred to as permissioned, and hybrid blockchain [26].

– Public blockchain: this classification allows anyone to join and participate in the network. Bitcoin is the most common example of a public blockchain where anyone can join and participate in the validation process [29].
– Private blockchain: unlike public blockchain, private blockchains impose restrictions on participation. Where only authorized and trusted entities are allowed to engage in activities within the blockchain [29]. This selective approach ensures that the chain's data is kept confidential and accessible only to the trusted participants, rather than being available to the public [30].
– Hybrid blockchain: it combines the characteristics of public and private blockchain. Some features can be open to everyone, while others are restricted access [18].

3.3. Blockchain transactions

Blockchain technology is implemented based on certain procedures, as Figure 6 describes how to work transactions in a blockchain, that starts with the request for the transaction and ends with the proof of the transaction, thus creating the block and linking it to blockchain. The process begins when someone requests a transaction, then the requested transaction is broadcasted to others over the network using peer-to-peer, where each node adds data to its record and forwards it to all other nodes, i.e., communication is made between nodes without the need for a central node [24]. Then, the nodes validate the transactions and the user's state using one of the well-known consensus algorithms, which we discuss later, once the transaction is verified, it is combined with other transactions to create a new block of data, thus the new block is added to the existing blockchain to be permanent and immutable [7].

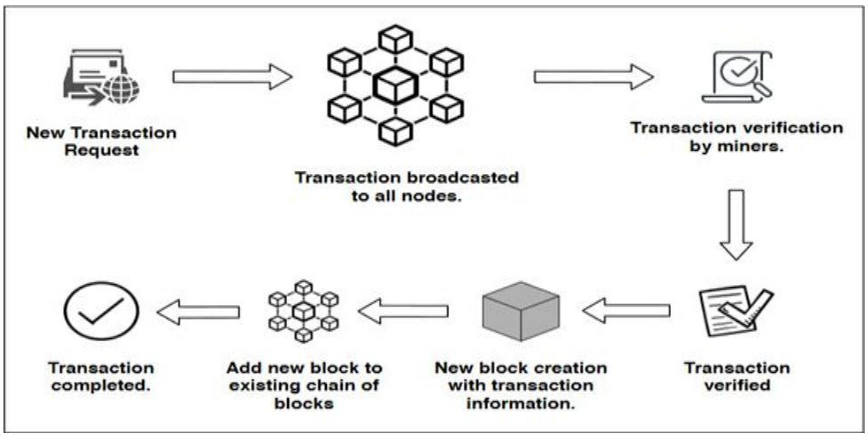

Figure 6. Transaction workflow [31]

3.4. Consensus mechanisms

Consensus is a main method in blockchain technology that is based on establishing consensus between several parties regarding the validity of the block and the data stored in it [18]. In blockchain, consensus is required to prevent modification and to ensure transactions. There are several consensus algorithms that can be used in a blockchain, such as proof of work (PoW), proof of stake (PoS), and delegated proof of stake (DPoS) [32].

The first and most well-known consensus mechanism is PoW which is based on mining that requires nodes to solve complex mathematical problems to validate transactions and add new blocks to the chain [33], where blockchain runs in a network of computers called “miners” [28]. In more detail, when the transactions are requested, the miners receive the request transactions, and then, miners race to solve challenges, new transactions take approximately 10 minutes, after that, one of the miners solves the challenge first, on the other hand, the rest of miners community verifies the validity of the new block mined, then the new transactions are added to the blockchain, lastly, the winning miner earns a reward for solving the challenge first.

Instead of solving a complex mathematical problem where there are no miners like PoW, there is another consensus mechanism called PoS [34]. This mechanism is based on the concept of “stake”, validators are chosen to add new blocks to the blockchain based on the number and stake of the coins they own, i.e., the choice of validators is based on their relative stake in the coin [25].

By implementing various consensus mechanisms, blockchain networks can ensure that nodes within the distributed system reach an agreement on the state of the ledger. This agreement helps prevent fraud, and tampering and maintains the integrity of the recorded transactions.

3.5. Smart contract

Due to the distributed nature of blockchain among users, it enables the deployment of pieces of software to a wide range of next-generation decentralized applications without the involvement of a trusted third party, this is known as smart contracts [35]. Thus, smart contracts are executable computer programs that automatically and independently execute contracts, without the need for human intervention. Smart contracts are based on blockchain technology to provide transparency, security, and effectiveness in the implementation of contracts, and work to convert the terms and conditions agreed upon in the paper contract into software codes that are executed automatically [36]. Smart contracts are programmed using blockchain-based programming languages such as solidity on the Ethereum platform [35]. Smart contracts are distributed across the blockchain network where they are stored and executed on multiple machines in blockchain, making them decentralized and tamper-proof. Figures 7 and 8 provides an overview of smart contracts in blockchain technology.

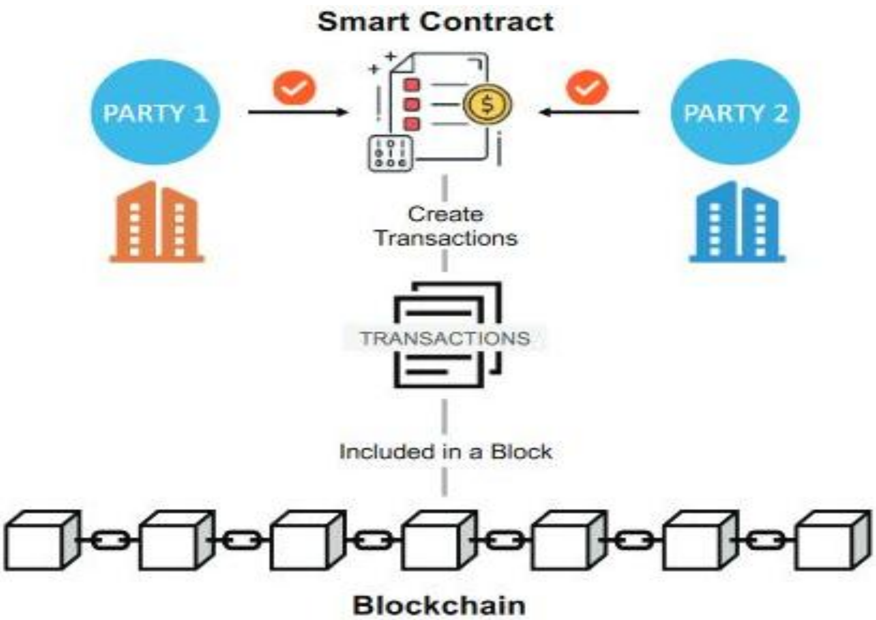

Figure 7. Smart contract for blockchain [37]

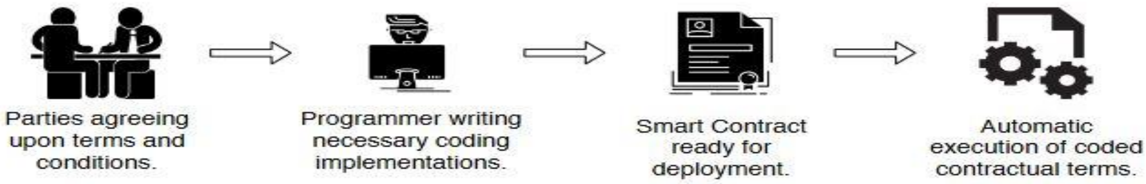

Figure 8. Steps to build a typical smart contract [31]

4. BLOCKCHAIN APPLICATIONS IN SMART GRID SECTOR

The unique features of blockchain, such as transparency, distributed data storage, security, and decentralization, have driven its acceptance by users [27], contributing to its widespread adoption. These features enable blockchain to offer significant advantages to the electricity system, whether in conventional or SGs, particularly by enhancing scalability and supporting decentralized operations. Notably, blockchain eliminates the need for intermediaries, facilitating direct transactions between prosumers and consumers. This paper explores innovative applications, proposed models, and blockchain-based projects within the SG sector.

Agung and Handayani [18] proposed an architecture that uses blockchain to manage transactions and ensure that they are executed between the consumer and the generator in an unchangeable or modified way. Also, the authors developed a mobile app to use between the consumer and the system. The authors introduced a scenario based on a set of clusters (A, B, C, D, E, and F), assuming that cluster A is government-owned power plants, and cluster B is residential buildings that draw energy from cluster A, otherwise, the authors assumed that cluster C and E are residential buildings but some of them capable of generating energy from renewable energy sources, cluster D is privately owned power plants, also cluster F is a public power supply station, and grid storages to store excess electricity on the grid.

In addition to that, based on the existing electrical grid, the authors considered each entity is a node where it is a provider with a light node, which is a small computing device instead of the existing electricity meters, to reduce the complexity and high cost of the hardware requirement, its work is to create an address and maintain the balance of this entity or address. Then the authors add full nodes at the existing distribution points (for each cluster). Moreover, full nodes provide security for the electricity supply based on validating transactions, maintaining consensus, routing across the grid, and determining an efficient route for electricity delivery.

In general, this study showed that presented the proposed model from a broad perspective, where the process of buying and selling via blockchain technology was clarified. Although maintaining the stability and traceability of transactions in addition to competition in the market for the presence of many producers, anyone with high-performance computing devices could control the system.

Tanaka *et al*. [38] suggest an approach that can increase the efficiency of electricity trading, reduce costs, and promote the use of renewable energy sources. They developed a system in which energy can be exchanged based on blockchain so that energy exchanges can be conducted in a peer-to-peer manner, on a private Ethereum blockchain, with different conditions. The proposed system consists of two main components: digitalgrid routers and blockchain technology. A digitalgrid router is a device that manages energy flows and exchanges between electricity prosumers and consumers. The system works by storing data about energy production and consumption collected by the smart meter in the blockchain.

Accordingly, the approach based on blockchain can enable more efficient trading of electricity by allowing prosumers and consumers to exchange energy directly without the need for middlemen (third party), thus this can reduce transaction costs, and increase the transparency and traceability of energy trading. However, the proposed system is complicated due to the use of two main components: digitalgrid routers and blockchain technology.

Mengelkamp *et al*. [39] present a new framework for the local energy market (LEM), specifically designed to exchange electricity generated by household solar panels. It uses a private blockchain network to create a local energy market. Based on an open-source application, the market is designed and simulated for 100 residential households to supply energy to consumers. Energy and its consumers with a decentralized platform for local energy trading, thus eliminating dependence on central intermediaries. In more detail, the core of this system is a unique auction-based market, with well-defined periods for market transactions and a uniform pricing system for each period. The market pricing structure is designed with upper and lower price thresholds based on network interactions to maximize demand and supply. In cases where contractual obligations are not fulfilled due to inaccurate forecasting, the responsible party is obliged to compensate at pre-determined higher network prices. An interesting aspect of their model is the assumption that energy-related taxes and fees are proportional to the price of electricity, providing a potential simplification in financial calculations. Additionally, consumption and production data are accurately tracked and forecasted using smart meters, with surplus or deficit information sent to blockchain-based accounts. While the study is pioneering in its approach, it is important to note that the simulation's scope, limited to 100 households, may not encapsulate the complexities of larger or more diverse energy markets. Additionally, the economic evaluation provided is preliminary and warrants further in-depth exploration.

Aggarwal *et al*. [40] proposed the energy chain system, a system for secure and decentralized energy trading using blockchain technology so that it can execute contracts and deal with transactions between commercial parties. The proposed model works through three stages: the miner node is selected based on the power capacity of different smart homes, created and validated block, and finally, a secure transaction is made for SG energy trading. The authors proposed a scenario to show the connection devices of the SG, in addition to explaining the processing of requests for smart meters in the network using blockchain technologies. Also, suppose that there are two types of nodes, normal and miner nodes. The miner node is used to authenticate and authorize transactions that occur in the network. Otherwise, the normal nodes perform as an authority to coordinate and verify transactions. Once transactions are authenticated by a metal node, they are broadcast to the network.

In the above-proposed system, the first major task of implementing a blockchain in a SG ecosystem is to select a miner node from the set of nodes in a smart home. This is done by a proposed algorithm so that the number of active nodes within the SG is calculated, then each active node's power capacity is checked and compared to the threshold value. The miner is declared by the active node in which the active node's power capacity is greater than the threshold value, otherwise, it is a normal node. Accordingly, due to the use of miners in energy chain, the consensus mechanism used is the PoW. Based on that, the first miner to solve the mathematical problem can create a new block that is validated by other nodes, thus getting the reward for solving this problem.

However, the mentioned study does not address how the proposed system can enhance trust and prevent counterfeiting issues in SGs, which is the main focus of the current study. Additionally, our study proposes a new framework for enhancing trust and preventing counterfeiting issues for the SG, which may differ from the energy chain system in terms of its approach and methodology. Therefore, the gap between the two studies lies in the focus and methodology, where our study aims to address the challenges related to trust and counterfeiting in SGs using blockchain technology, while the energy chain system focuses on decentralized energy trading using blockchain technology with a different consensus mechanism.

In another study Mengelkamp *et al.* [41] proposed a new framework called Brooklyn microgrid (BMG) in which consumers and prosumers can trade self-produced energy in a peer-to-peer manner and thus enable them to trade energy within the community. So, the authors derived seven different components of a market which are microgrid setup, information system, grid connectivity, management trading system energy, pricing mechanism, market mechanism, and regulation. The proposed system architecture consists of two main components as the virtual community energy market platform and the physical microgrid, through which community members can trade locally generated energy using P2P with their neighbors. Practically, the virtual community energy market platform provides the technical infrastructure for the local electricity market, moreover, it depends on a private blockchain using the 'Tendermint' protocol. On the other hand, the physical microgrid acts as a back-up to prevent outages so that a small electrical grid is created, which consists of 10 by 10 housing blocks, in addition to the existing distribution network, through which some critical sectors, like hospitals, receive energy at fixed rates.

BMG uses the conventional grid operated by the independent system operator to supply the physical power flow and disconnect the physical microgrid only in emergencies. The information is transmitted through the virtual layer, while all power flows occur on the grid infrastructure. Then, consumption and generation data from the participants' "Transactive Grid" smart meters are transmitted to their blockchain accounts. Thus, buy and request orders are generated according to this information, and the request is sent to a market mechanism powered by a smart contract. Once the matching is complete, the payment is made, and a new block is added to the blockchain which includes all current market information. The transactions made are also sent to the respective agents via their blockchain accounts.

Liu *et al*. [42] presented a blockchain framework for managing the interaction between electric vehicles (EVs) and SGs through EV charging with a focus on enhancing reliability and efficiency supported by blockchain technology. The authors determine stakeholders in the grid system include large conventional power plants, small distributed renewable energy generators, and energy stores that make up the electricity supplier side as well as the blockchain network in which electricity supply and demand information is transmitted, encrypted, and stored. In this study, on the one hand, the system is designed based on the public blockchain network on the other hand, a programmable charger to verify the charging and discharging processes is installed, where the EV is able to interact with the SG blockchain platform in terms of publishing and transmitting the charging or discharging transactions. In this model, transactions such as buying or selling are made by EV owners via a blockchain platform and once the customer's identity is identified, the order is processed and then published across this network for verification and saving in a distributed manner.

This approach ensures secure transactions between EVs and the SG, thus increasing the security of transaction exchange and enhancing trust among stakeholders due to its reliance on blockchain technology. However, this study faces a scalability problem in the event of large amounts of data, in addition to the need for this system to have great experience due to the level of complexity of the system. Also, the system only addresses one party, the EVs, while the rest of the parties are ignored.

Erturk *et al*. [43] investigate the impact of blockchain technology on smart energy systems, highlighting both positive and negative factors. The authors address the uncertain impact of blockchain on transaction costs within smart energy applications. The researchers recommend focusing on economic feasibility and transaction costs in future studies to make blockchain applications more suitable for the SG. In this study, the researchers limited themselves to reviewing the literature from an academic point of view, and no SG framework was implemented based on blockchain technology. The researchers also relied on reviewing studies during the period from 2016 to 2019.

Alladi *et al.* [44] highlighted the application areas of blockchain in the SG, the researchers discussed the integration of blockchain technology into the SG by studying and reviewing many use cases in the literature related to this field. Besides, this study explained the blockchain architecture and block structures for each part. Although the study discussed the stability of data in blockchain technology, and enhanced security by reducing cyber-attacks, this study did not provide an actual framework through which a system could be implemented and was limited to the theoretical aspects of the field of SGs based on the blockchain.

O'Donovan and O'Sullivan [45] provided a systematic analysis of blockchain applications in the energy sector. Their research methodology is based on three layers: upper layer, middle layer, and lower layer, as these multiple layers are used to evaluate real-world energy blockchain initiatives. In more detail, the upper layer of the study targets systematic peer-reviewed studies and aims for a comprehensive understanding of the applications. While the middle layer only evaluates real-world applications by reviewing the extracted projects and applying inclusion/exclusion criteria, the bottom layer delves into objective analysis by generating metadata about real-world applications, providing an exploration of the practical deployment of blockchain in the field energy. Since the study follows a novel approach in its methodology, it provides a comprehensive understanding of the various blockchain technology initiatives in the energy sector. However, the study did not provide a new practical framework for the energy sector.

Andoni [46] provided an overview of blockchain technology in terms of architecture, block structures, and consensus mechanisms. This study provided a comprehensive survey of the blockchain-based SG sector, where 140 studies for energy sector applications were reviewed. Researchers discussed several use cases in terms of the pros and cons of each application in blockchain technology. The study showed that most applications are in the growth stage and need research and development, especially in the areas of scalability, enhancing trust, and preventing counterfeiting problems. This study lacks a real and practical framework that can be relied upon in the energy sector and SGs.

Afzal *et al*. [47] proposed a new distributed demand-side management system for a community microgrid that integrated smart meters, renewable energy sources, and blockchain technology. The system used a game approach to minimize the cost of electricity for individual homes and the entire community. Smart home users optimize their daily energy consumption by applying their best strategy to minimize energy consumption costs while maintaining the privacy of their energy consumption. The system is distributed on a blockchain, which enables autonomous monitoring of smart appliances and the billing of electricity consumption through smart contracts.

Overall, the mentioned study presents an innovative approach to energy demand-side management that addresses the challenges of distributed renewable energy sources and real-time energy trading in a community microgrid. The proposed system's use of blockchain technology provides a trusted communication medium between participants and ensures the autonomous monitoring of energy consumption. However, implementing such a system requires considerable computational resources and can present scalability challenges within the current energy infrastructure. Consequently, more research is necessary to investigate the viability and efficacy of a blockchain-enabled SG system for addressing trust and security concerns in the energy sector.

Swain *et al*. [48] proposed a model based on interconnection energy self-sufficient households with prosumer communities to generate, consume and share clean energy on a decentralized trading platform by a SG with integration blockchain technology. As the main goal of smart cities lies in making use of the available resources in terms of reducing energy and operational costs, which contributes to improving the lives of residents. However, the long distances between the sensor nodes and the base station can lead to very large consumptions of sensor power and thus reduce the network lifetime, so the authors propose a new approach based on a bio-inspired algorithm in particular particle swarm optimization (PSO) and a genetic algorithm to obtain the shortest path and increase network performance (system), which can extend the life of the network by significantly reducing power consumption.

The authors also emphasize the significance of ensuring data privacy and communication network security by integrating blockchain technology into the SG. This proposed model facilitates sustainable energy usage and promotes the adoption of renewable energy sources within microgrids, aligning with the overarching objective of establishing sustainable smart cities. However, the limited scalability of blocks handicaps their capacity to handle substantial data volumes effectively. As a result, utilizing these blockchains can lead to substantial resource consumption and increased energy usage within the network due to prolonged processing times and long communication distances. Addressing these energy consumption concerns and optimizing energy efficiency have become critical factors influencing the network's longevity.

Doan *et al*. [49] proposed an innovative peer-to-peer energy trading scheme within a SG framework. In this model, residential units (termed 'prosumers') turn into either buyers or sellers of energy, contingent upon their immediate energy production and consumption patterns. In more detail, the proposed model employs an auction-based approach for energy trading. The system operator likened to an auctioneer, supervises the game while the prosumers dynamically adjust their energy buying or selling decisions based on fluctuating prices. Utilizing blockchain as the backbone of this framework, they explain how this technology could enhance transparency and security, and streamline efficiency in energy transactions. The innovative model of a double auction scheme, underpinned by game-theoretic principles, aims to foster a competitive and equitable marketplace for energy trading based on blockchain. A significant leap in this system is the deployment of blockchain technology, specifically Hyperledger Fabric. This choice facilitates real-time trading, efficient user management, and data privacy.

Accordingly, while the proposed peer-to-peer energy trading system using a game-theoretic model and blockchain technology offers considerable benefits as previously mentioned, certain potential drawbacks must be considered such as the system's efficiency relies heavily on real-time trading, which could be problematic if there are delays in the network or technical glitches, impacting the system's reliability.

Hasankhani *et al*. [50] provided an in-depth study and comprehensive review of applications of blockchain technology in the field of SGs and provided comparisons based on an extensive literature review. The authors emphasize the increasing necessity of decentralized energy management and secure economic data transactions in SGs. The authors carefully categorize applications of blockchain technology in diverse areas, including smart contracts, demand response (DR), EVs, internet of things (IoT), decentralized energy management, energy trading, and financial transactions. Despite its comprehensive scope, the study's insights are inherently limited by the scope of the literature reviewed and do not delve deeply into empirical data or practical applications. However, the review represents an essential contribution, particularly for research endeavors that seek to explore and innovate within the relationship between SG systems and blockchain technology.

Dehalwar *et al*. [51] presented a new study that focuses on implementing blockchain technology for self-sovereign identification and authentication in the SG. It addresses the security challenges posed by deploying information and communication technologies in the grid and proposes a blockchain-based approach to minimize identity-based security breaches. The study suggests a Merkle tree architecture for blockchain implementation in the distributed electrical energy network. This architecture enables easy verification of energy at nodes and transactions by traversing the path of the Merkle tree. Hash functions and SHA 256 are utilized for hashing and data integrity. The proposed approach was developed as three stages: interface development, blockchain platform based on Hyperledger, and using a consensus mechanism which is called Byzantine fault tolerance to add the new device. As presented in this work, although the use of blockchain technology in the SG shows promising potential for enhancing cybersecurity and revolutionizing energy operations and market mechanisms in the electricity sector, the performance of mining may be reduced when some nodes crash.

In the study presented by Falahi *et al*. [52] proposed an advanced system that uses blockchain technology to operate SGs known as TESTBED2, where they highlighted the potential of blockchain technology, especially in enhancing the operations of these SGs in terms of security and trust between participants and high reliability. Although the authors presented a comprehensive analysis of the system's performance and explained the details of the system based on blockchain technology for SGs, in terms of design principles, operating mechanisms, and potential applications in this field are indicated, the project was not implemented to fully function in the SG.

A new study based on blockchain was proposed by [53], the study's focal point is the privacy-centric blockchain-based electricity auction scheme it proposes for vehicle-to-grid (V2G) in a SG. The study elucidates the system's architecture, enumerates its design objectives, and details its construction. It outlines a model comprising five entities—EVs, charging stations, a trusted authority, an aggregator, and a blockchain. The study assumes the trusted authority to be entirely trustworthy and the aggregators to be honest yet curious. It also considers the presence of an external adversary who might spy and eavesdrop on communication channels and record transactions on the blockchain. In addition, the goals of the design proposed system revolve around the authentication and privacy of EVs and charging stations, auction privacy, traceability, and accountability. The authors underscore the need for the authentication of EVs and charging stations, maintaining their privacy, ensuring auction privacy, and providing traceability and accountability. As presented, the study focuses on EV technology while neglecting other aspects of SGs.

A comprehensive literature review is presented in [54], where the authors stated that they critically analyzed 92 research publications to evaluate the impact of blockchain technology on SGs and distributed energy resources and the importance of including conference papers in their review, as they often contain new research ideas and approaches, especially in blockchain technology. Although the study is comprehensive and well-researched, as it includes a large-scale review of a large number of publications, the scope and ideas of the study were limited to the data available in the publications reviewed and did not provide an actual framework that could be relied upon.

Waseem *et al*. [15] provided an overview of the work of the SG and the studies presented in this field, as they discussed blockchain technology from the point of view of its potential efficacy and benefits in SG settings, especially in the field of cybersecurity, where many important cyberattack models were presented, and demonstrated strategic defensive ways to encounter these attacks. The researchers concluded that the SG based on blockchain technology still requires further study and research in this field. Therefore, this study may help researchers choose their directions in this field to prevent future aggravation of cyber attacks on this sector and focus efforts on developing SG applications in real communities.

Lampropoulos [55] presented a new study that included a large-scale bibliometric analysis that included more than 1,000 scientific documents published on the Scopus and WoS databases during the period from 2015 to 2022. The study included drawing scientific maps and conducting statistical analyses in terms of annual scientific production, authors, countries, and the most common keywords in research studies. Although this study did not provide a new practical framework as it was limited to conducting a bibliometric analysis of these studies, it concluded that there is an urgent need to conduct more experimental and applied studies centered on SGs and their integration with blockchain technology.

5. DISCUSSION

This section highlights the contributions of various studies to the development of blockchain-based SG frameworks, each addressing specific challenges and employing distinct implementation methods. Studies [18], [38] proposed solutions for security and decentralized trading issues, while studies [39]-[42] tackled scalability and distribution challenges. Additionally, studies [47], [48] focused on renewable energy management and demand monitoring, and studies [49], [51]-[53] explored privacy and security in complex systems. However, other studies included in this review primarily focused on literature analysis without presenting proposed frameworks.

It is evident that each study targets a particular aspect of blockchain applications in SGs, such as security, privacy, or scalability, or applies specific methods like auctions, peer-to-peer systems, or self-authentication techniques. Based on the analysis of the advantages and disadvantages summarized in Table 3 (in Appendix), it is clear that these frameworks address individual challenges without considering an integrated approach to resolving multiple issues simultaneously.

Future research could benefit from synthesizing the strengths of these studies while addressing their limitations. For example, scalability-focused models like those in studies [39], [40] could be combined with privacy-enhanced frameworks such as those in studies [49], [51], [53] to create systems that are both efficient and secure. Similarly, integrating decentralized trading mechanisms from studies [18], [38] with the robust demand-monitoring capabilities of studies [47], [48] could support real-time peer-to-peer energy trading, adapting dynamically to market needs and renewable energy fluctuations.

The ultimate goal for future research should be the development of a unified blockchain-based framework that comprehensively addresses the core challenges of security, privacy, scalability, and energy management. Such a framework has the potential to revolutionize SG systems, enabling secure, efficient, and decentralized energy markets that fully exploit the advantages of blockchain technology.

Finally, our comprehensive review of recent and relevant studies revealed significant progress in enhancing trust and preventing fraud in SGs using blockchain technology. While some systems have been successfully implemented in real-world applications, others remain theoretical or in the prototype stage. These findings underscore the potential for further advancement and innovation in this field.

6. CONCLUSION

This paper highlighted the unique features of blockchain technology that have driven its widespread acceptance across various sectors, particularly in the energy domain and SGs. We provided an overview of conventional and SGs, emphasizing the challenges faced by conventional grids and how SGs address these issues. However, the practical implementation of SGs introduces concerns related to trust, security, transparency, transaction tracking, and inefficiencies caused by third-party involvement. To address these, we reviewed blockchain technology, which operates without the need for intermediaries.

Additionally, we explored blockchain-based applications in SGs, examining their mechanisms, advantages, and limitations. The study showcased the progress achieved in this field, with some systems implemented in real-world scenarios while others remain conceptual or at the prototype stage. We analyzed these studies to highlight their strengths and weaknesses.

This research reflects optimism about the potential for further advancements in blockchain-based SGs. As a future direction, we aim to develop a new framework and consensus algorithm to build an enhanced blockchain-powered SG system.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study were generated and used through a simulation that was carefully to reflect real-world scenarios.

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APPENDIX

Table 3. Comparison between SG studies based on blockchain technology

Ref.	Contributions	Advantages	Disadvantages
[15]	They discussed blockchain technology from the point of view of its potential efficacy and benefits in SG settings, especially in the field of cybersecurity.	Cyber attacks that could affect the operation of SGs based on blockchain technology were investigated.	Lack of practical framework.
[18]	Proposed an architecture that uses blockchain to manage transactions between consumers and generators, developed a mobile app for consumer-system interactions.	Ensures that transactions are unchangeable or modified, enhances trust and security, provides transparency and traceability.	The system may be controlled by individuals with high-performance computing devices.
[38]	Developed a new system for peer-to-peer energy exchange based on blockchain.	More efficient electricity trading, reduced transaction costs, increased transparency, and traceability.	The proposed system is complicated because of using two main components: digital grid routers and blockchain technology.
[39]	Present a new framework for the LEM, specifically designed to exchange electricity generated by household solar panels based on blockchain and implement based on open-source project.	Provides transparency and reliability between stockholders.	Faces scalability issues. The simulation's scope, limited to 100 households. The evaluation provided is preliminary.
[40]	Introduced the energy chain system for secure and decentralized energy trading using blockchain.	Can execute contracts and handle transactions between commercial entities.	Did not address how the system can enhance trust and prevent counterfeiting issues in SGs.
[41]	Proposed a new framework called Brooklyn Microgrid for trading self-produced energy in a peer-to-peer manner within a community.	Enabled local trading of energy using P2P with neighbors, and enhances community energy self-sufficient.	Reliance on a private blockchain using the 'Tendermint' protocol may have limitations in terms of scalability. Scalability issues prevent the size of blocks from expanding significantly.
[42]	Presented a blockchain framework for managing the interaction between EVs and SGs through EV charging processes, with an emphasis on enhancing reliability and efficiency.	Secure transactions between EVs and the SG, increasing the security of transaction exchanges. Implementation of a programmable charger to verify charging and discharging processes, enabling direct interaction between EVs and the SG blockchain platform.	The study encounters scalability issues with large amounts of data. The system requires significant expertise due to its level of complexity. The model focuses only on one party, the EVs, while other stakeholders in the SG system are not addressed.

Table 3. Comparison between SG studies based on blockchain technology *(continued)*

Ref.	Contributions	Advantages	Disadvantages
[43]	Investigated the impact of blockchain technology on smart energy systems, highlighting both positive and negative factors.	The study clarified the potential impacts, whether positive or negative, of blockchain technology on the smart energy sector.	The study is limited to a review of literature from an academic point of view, as studies were reviewed during the period from 2016 to 2019. No SG framework based on blockchain technology was implemented.
[44]	highlighted the application areas of blockchain in the SG, the researchers discussed the integration of blockchain technology into the SG by studying and reviewing many use cases in the literature related to this field.	Enhance security in terms of cyber-attacks.	Did not enhance trust and did not prevent counterfeiting issues. No SG framework based on blockchain technology was implemented.
[45]	Provided a systematic analysis of blockchain applications in the energy sector.	Provides a comprehensive understanding of the various blockchain technology initiatives in the energy sector.	Not address enhancing trust and preventing counterfeiting issues. Not provide a new practical framework for the energy sector.
[46]	Provided a comprehensive survey of the blockchain-based SG sector.	Provided a general understanding of the energy sector based on blockchain technology. Discussed many of the challenges facing the development of this sector based on blockchain technology.	Lacked a practical framework that can be relied upon in the energy sector and SGs.
[47]	Proposed a distributed demand-side management system for a community microgrid integrating smart meters, renewable energy sources, and blockchain.	Addressed the challenges of distributed renewable energy sources and real-time energy trading. Ensures the autonomous monitoring of energy consumption.	Requires significant computational resources and may pose challenges in terms of scalability and interoperability.
[48]	Proposed a new model based on interconnection energy self-sufficient households with prosumer communities.	Sustainable use of energy and promotes the use of renewable energy sources.	Scalability issues prevent the size of blocks from expanding significantly, making them unsuitable for storing and processing large amounts of data. Blockchains can consume huge amounts of resources and increase the overall capacity of the network.
[49]	Proposed a peer-to-peer energy trading scheme within a SG framework. The proposed model employs an auction-based approach for energy trading.	Enhanced transparency, security, and efficiency in energy transactions.	Efficiency relies heavily on real-time trading, which could be problematic if there are delays in the network or technical glitches.
[50]	In-depth analysis of various applications of blockchain technology in SGs.	Covers a wide range of blockchain applications in SGs, provides clarity and ease of understanding through structured categorization, and highly relevant to current and future research in the field of SGs and blockchain technology.	Insights and conclusions are confined to the reviewed literature. Does not provide a framework
[51]	Implementing blockchain technology for self-sovereign identification and authentication in the SG.	Handled the security challenges posed by deploying information and communication technologies in the grid.	Performance of mining may be reduced when some nodes crash.
[52]	Proposed an advanced system (TESTBED2) that uses blockchain technology to operate SGs.	Enhanced the operations of SGs in terms of security and trust.	The project was not implemented to fully function in the SG.
[53]	Focused on a privacy-centric blockchain-based electricity auction scheme for Vehicle-to-Grid (V2G) in SGs.	Ensured the authentication and privacy of EVs and charging stations, auction privacy, traceability, and accountability.	While this study focused on V2G, it neglected other aspects of SGs.
[54]	They critically analyze 92 research publications and provide a comprehensive view of the impact of blockchain technology on SGs and distributed energy resources.	Resource for future research. The study is comprehensive and well-researched	Limited by reviewed studies. Lack of practical framework.
[55]	The researcher presented a new study that included a large-scale bibliometric analysis that included more than 1,000 scientific documents published on the Scopus and WoS databases during the period from 2015 to 2022.	The study indicated the need to conduct further studies in the field of SGs based on blockchain technology.	Lack of practical framework. Limited to mathematical and statistical analysis procedures.

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