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Review

Status, Challenges and Future Directions of Blockchain Technology in Power System: A State of Art Review

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Abstract: Intermittent distributed energy resources (DERs) add challenges to the modern power system network. On the other hand, information and communication technology (ICT) is changing traditional electricity grids into smart grids, which facilitates a decentralized system in which prosumers may participate in energy trading. Smart grids, DER integration, and network connectivity are adding complexity to the power system network day by day; Blockchain technology might be a great tool to manage the network's operational complexity. The Blockchain provides for quicker, frictionless, secure, and transparent transactions. With the addition of smart contracts, it may be utilized to manage the expanding complexity of the contemporary power system. In this study, the authors focus on the scope, challenges, and potential future direction of Blockchain technology application in the power system. Blockchain has received interest and has been used for decentralized power system applications in recent years, but it is still young and has scalability, decentralization, and security concerns. This article discusses the interfaces and the possibilities that can assure trust, security, and transparency in decentralized power system applications and make a decentralized power system and power market possible.

Keywords: Blockchain; cryptography; consortium; Digital Ledger Technology; distributed energy resources

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1. Introduction

It was in the year 1991 when the research scientists Stuart Haber and W. Scott Stornetta offered a computationally feasible time-stamping method for digital documents that could not be backdated or tampered with. They did this by developing a system to store time-stamped documents that uses the concept of a cryptographically protected chain of blocks [1]. This was the beginning of the history of Blockchain. In 2008, a person using the pseudonym Satoshi Nakamoto issued a white paper [2] that described a system for peer-to-peer transactions using bitcoin. This was the first time that Blockchain found its most suited and viable use, and it became a craze throughout the world [3]. The next digital revolution is one that has the potential to have an even greater impact than the internet [4]. The use of Blockchain technology is on the increase; it is revealing its possible applications and advantages in a variety of industries, including the following: banking [5], agriculture [6], health and medical science [7], real estate [8], entertainment [9], smart cities [10], and many more. In spite of the fact that the use of Blockchain technology is just in its infancy stage, the research platforms are demonstrating consistent development. A total of 143,716 papers (till 25 September 2022) on a variety of study topics were found when a search using the term "Blockchain" was performed on the Scopus database. Figure 1 illustrates the trend that can be noticed in the research articles that are based on Blockchain technologies. As can be seen in Figure 1, the investigation into and use of the Blockchain concept in a variety of settings is continuously advancing. The research activities on Blockchain were identified before

2013, but with a negligible number; an exponential growth can be seen only after 2013. This is true across the board. Similarly, Figure 2 provides the trend of research publications in which Blockchain technologies is implemented in the domains of Electrical and Electronics Engineering. There are different sectors that use this concept; however, the objective is to present these two figures to show the increasing trend of Blockchain technologies in research and development activities.

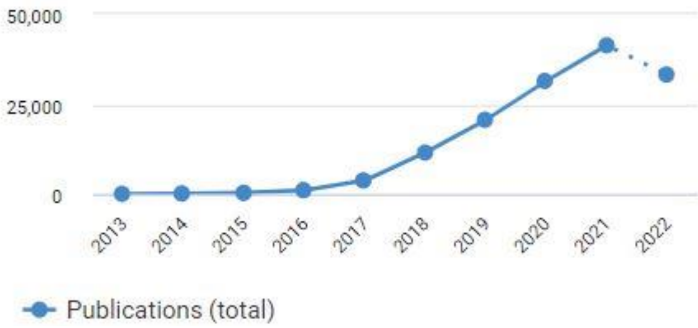

Figure 1. Trend of research publication with Blockchain technology (From 2013 to September 2022).

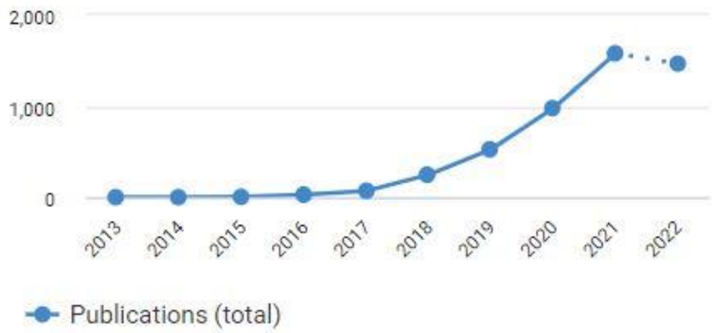

Figure 2. Trend of research publications with Blockchain technology in the domains of Electrical and Electronics Engineering (From 2013 to September 2022).

Focusing on technical detail, a Blockchain is an open distributed ledger that is accessible to all and can efficiently record transactions between two parties, and these records in the blocks are immutable [11]. In the case of electricity, utilities have the objective of offering affordable and reliable electricity to their customers. The introduction of distributed energy resources (DERs), such as photovoltaic (PV) systems that are intermittent, adds more complexity to the power system network [12]. In addition, the concept of smart grids, integration of DERs, and communication between the various components of the power system network is adding more complexity to the network, where technology such as Blockchain could be a powerful tool to manage the complexity of today's modern power system network. The Blockchain allows for faster, seamless, secure, and transparent transactions, and with the introduction of smart contracts that add automation to Blockchain technology, it can find potential applications well beyond cryptocurrency and can be used to cope with the rising complexity of the modern power system. The number of active enterprises using Blockchain technology in the energy sector is continually increasing [13]. It is being used in the energy industry by companies and pilot projects all around the globe, including P2P energy trade, wholesale and retail energy markets, and energy commodity trading [14].

The introduction and advancement of information and communication technology (ICT) are transforming traditional power grids into smart grids, and eventually into a decentralized system in which prosumers can actively participate in energy trading [15]. In this context, Blockchain is emerging as a powerful technology for energy trading and has attracted the growing attention of many scholars. Apart from the energy markets, Blockchain also finds application in power flow studies of microgrids, demand response, electric vehicles (EVs), and so on. Blockchain, in conjunction with smart contracts, can enable operations and process control with the least amount of intermediary intervention, and its further application with artificial intelligence (AI) and machine learning (ML) will enable its potential application in smart grids in P2P energy trade, the plug-and-play interface of distributed energy resources (DERs), grid automation, distribution network management, and demand-side integration (DSI) programs [13,14]. Blockchain first popularized cryptocurrency trading and its characteristics make it a better tool for use in the electricity trade and other domains, which is why Blockchain technology is becoming increasingly popular in these sectors.

Using Blockchain technology for P2P energy trading will transform the centralized power market into a decentralized market. Blockchain technology will eliminate the market intermediaries, thereby providing privacy and security to both the consumers and prosumers in a microgrid. The formation of an energy trading platform on Blockchain technology is a hot topic and is an emerging one. It allows transparent and secure transactions of energy; however, it is still in its nascent stage and poses challenges and limitations related to performance, scalability, and interoperability. The issue is that, because Blockchain technology and its applications are still in their early phases of development in the field of power systems, their study is needed to fully comprehend the technology's capabilities and uses [16]. These limitations of performance, scalability, and interoperability are also known as the Blockchain trilemma [13].

The authors of this article make an effort to center their attention on the investigation and use of Blockchain technology within the context of the electricity system. The integration of a greater proportion of renewable energy sources (RES) into the grid is one factor that is contributing to the ever-increasing complexity of today's power infrastructure. The operational principles of a power system need to be updated in accordance with the dynamics of the RES that are involved and the characteristics of those sources [17,18]. At this point, the authors of this research are concerned about the path that the functioning of the power system will take in future and how secure it will be. This article, therefore, focuses more on the implementation of this emerging technology (i.e., Blockchain) in the contemporary electricity system, in which it discusses the difficulties that may arise and the potential applications of this idea in the years to come. Although later chapters go into more detail, the following are the primary contributions of this paper:

- Presents the concept of Blockchain technology, smart contracts, and various consensus algorithms in a simple way, which can be considered as study material for beginners.
- Presents the current scenario of the use of Blockchain technology in electrical power systems through research and development-related institutes.
- A state-of-the-art review of the prior works on Blockchain application in the electrical power system including energy trading, power flow studies, electric vehicles, demand side management, grid automation, security and privacy, and so on.
- Challenges and the way forward for the Blockchain application in future electrical power systems. Potential integrations of different technologies are also discussed, which could open the future direction for research.

At the beginning of this article, a general overview of the situation is presented, and then an explanation of the technology is given. In Section 2 of this article, a comprehensive introduction to Blockchain technology is provided. The algorithms used in Blockchain technologies, and the concept of smart contracts have been thoroughly discussed. The uses of Blockchain technology in power systems have been examined at length in Section 3. The opportunities and difficulties that lie ahead in the future are covered in Section 4. Finally, the study is concluded with concluding remarks.

2. Definition and Concepts

2.1. Overview of the Blockchain Technology

The Blockchain is a distributed, robust, chain-connected, ledger-sharing database, in which each node in the network is fault-tolerant and can achieve point-to-point communication [19]. Figure 3 portrays the basic understanding of Blockchain technology. The key characteristics of Blockchain technology are decentralization, distribution, encryption, security, and immutability [20]. It is called a Blockchain because it is a chain of blocks linked together by hash pointers. In certain ways, a single block is a ledger since it comprises a collection of transaction records. The fact that every node has a copy of the ledger is a crucial feature of this technology. When information is updated in a specific node's local copy, synchronization ensures that all other local copies are updated at the same time. Every local copy is, in a sense, identical. The main components of the block of a Blockchain are the header and body [21]. The block header contains the block number, the previous block's hash value, the current block's hash value, the timestamp, the nonce, and the creator's address [22]. Figure 4 shows the general structure of the Blockchain.

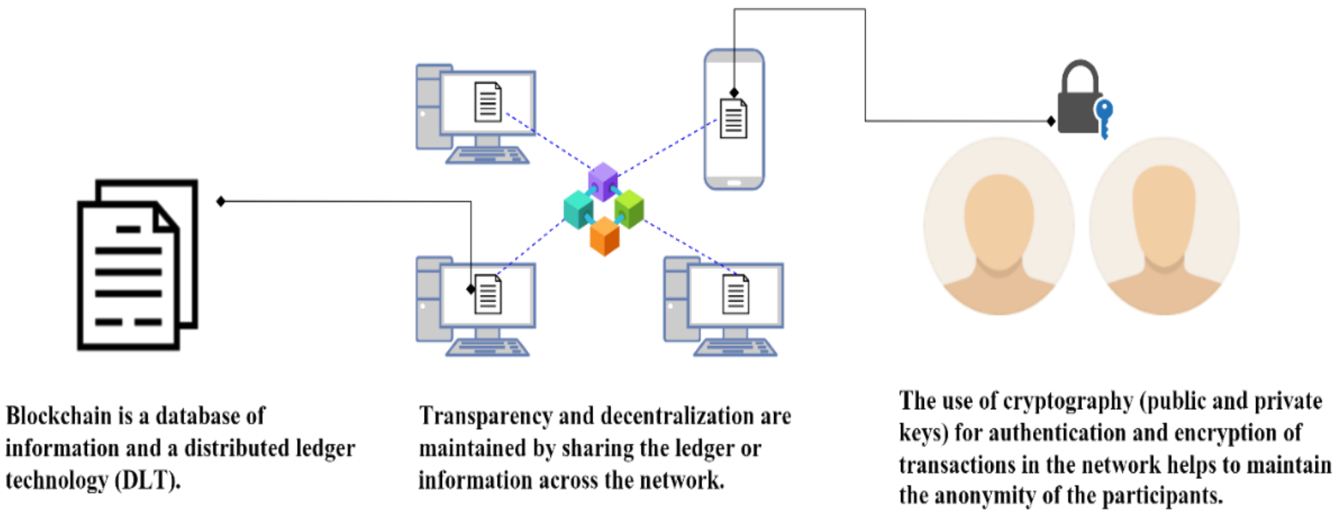

Figure 3. An overview of Blockchain technology.

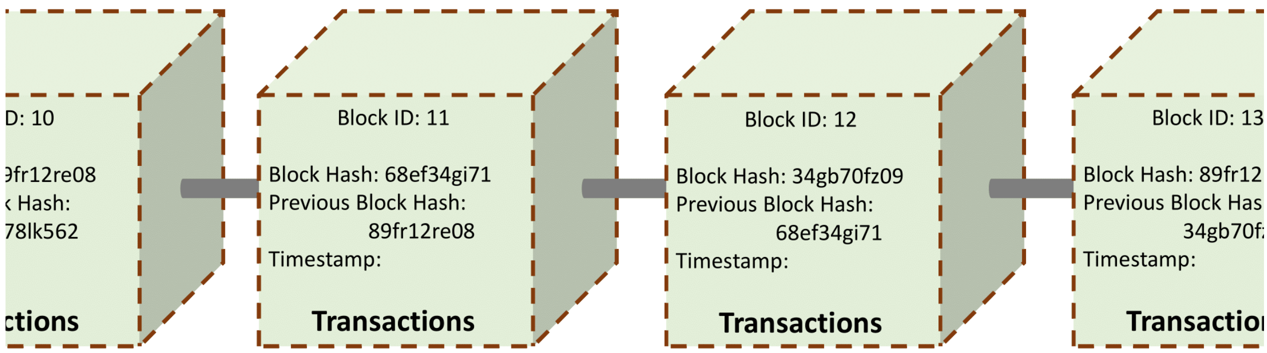

Figure 4. General structure blocks in the Blockchain concept.

Similarly, a Blockchain network's transaction is shown in Figure 5. User request for the transaction triggers the transaction to begin. Any cryptocurrency, contract, document, or piece of data might be used in this transaction. Then, across all of the peers in the network, this transaction is broadcast. Then, using one of the several consensus procedures, the transaction is validated. In the case of a Proof-of-Work (PoW) consensus mechanism, special nodes called miners are present in the network for the validation task. The transaction becomes immutable when it has been verified and posted to the Blockchain network. When a user or peer in the network begins a transaction, the transaction is eventually completed, and the process is repeated. As additional blocks are added to the Blockchain as a result of each transaction, the Blockchain becomes more secure and immutable [23].

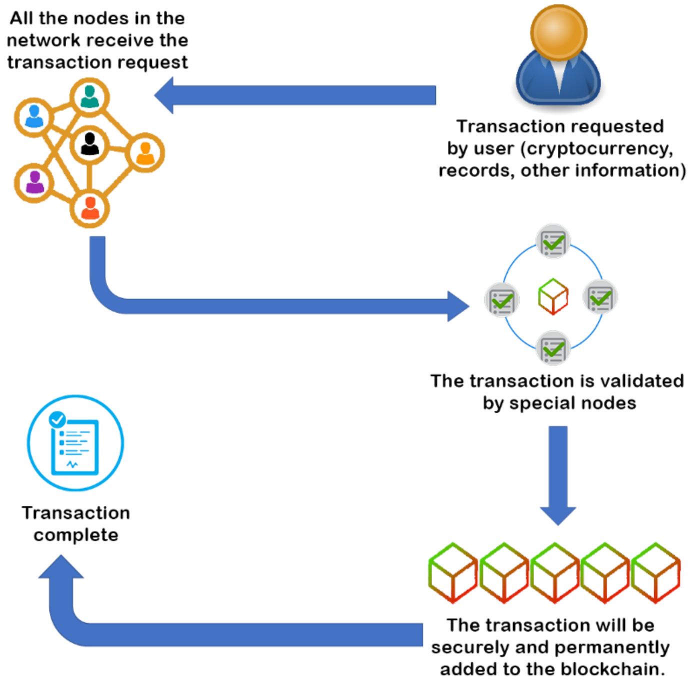

Figure 5. Transaction steps in the Blockchain network.

In cryptography, a hash function is a function that transforms data of any size to data of a specified size. A cryptographic hash function may quickly generate a hash for any input; however, deriving the input from the hash is challenging. Furthermore, any modifications to the original data would cause the hash to alter in a large and seemingly unrelated way [24]. The nonce is a value that the miner adjusts until a valid hash value for a new block is calculated [22]. In addition, Blockchain uses public and private keys for the authentication and encryption of the transaction [25]. Based on these authentications and encryption, the Blockchain is divided into different sub-divisions; Digital Ledger Technology (DLT) where Blockchain can be permissioned, permissionless, and consortium. Detailed descriptions of these consortiums are given in the upcoming sub-sections.

2.1.1. Permissionless Blockchain

A permissionless Blockchain is open for all users who want to participate in the Blockchain ecosystem. In the case of permission Blockchain utilizing a Proof-of-Work (PoW) consensus algorithm, all the users can view the data on the public Blockchain and take part in the consensus process for the validation of new blocks. It is a fully decentralized and transparent system that maintains the anonymity of the users with the help of public and private keys. In simple words, a public Blockchain is open to any user where participants can participate without explicit approval, and an example of such a Blockchain is Bitcoin and the public Ethereum network [2,25,26].

2.1.2. Permissioned Blockchain

A permissioned Blockchain is a distributed ledger that is confidential and is not publicly accessible. Only users with the appropriate permissions can access it. Users must authenticate themselves using credentials or other digital methods and are limited to the precise actions that have been permitted to them by the ledger administrators. Permissioned Blockchain allows trusted users or participants form the networks to record and validate the data. Permissioned Blockchain uses Proof-of-Authority (PoA), Proof-of-

Stake (PoS), Proof of Byzantine Fault Tolerance (PBFT), and Proof of Elapsed Time (PoET) consensus mechanisms for the validation of the blocks. The private Ethereum network and Hyperledger Fabric are examples of a permissioned Blockchain [26,27].

2.1.3. Consortium Blockchain

A consortium Blockchain is an incorporation of the permissionless and permissioned Blockchain [28]. It only allows the authorized users in the network to participate in the data reading and validating process. In the case of consortium Blockchain, the data is categorized as private and public data. In this Blockchain, the network can be designed to control a set of data to be public and a set to be private and this type of Blockchain is put into application to record cross-organizational business transactions [29].

2.2. Smart Contracts and Consensus Algorithm

Smart contracts are computer programs that implement real-world contract agreements, and these agreements are automatically executed when predefined conditions in the smart contracts are met. The data is written in the Blockchain only when the smart contract is executed [30]. In P2P energy trading, each node of the distributed energy system is given equal responsibility and plays the role of prosumer [31]. Smart meters are used in the DERs to maintain the load profile and to record the generation status from various sources, such as PV and battery-charge status. In the energy trading process, smart contracts are embedded in the smart meters for the execution of the energy trading as per the Blockchain framework [22]. The Blockchain uses an asymmetric hash algorithm where there is only the encryption process, and it implies that reversing the encrypted binary characters would not yield the original content; hence, it can prevent the rouge nodes from stealing information from the Blockchain [32]. The hash algorithm has randomness in it. This means that changing the information before the encryption slightly would result in hugely different encryption. Hence, it can prevent the information on the Blockchain from being easily cracked.

In a Blockchain network, miners are the special nodes responsible for validating the data block. For the agreement among the nodes or peers in the decentralized system, the Blockchain uses a consensus algorithm. The consensus algorithm is a process of reaching an agreement in a distributed process or system that ensures the information recorded by each node in the Blockchain is consistent with the consensus mechanism and employed in the absence of any central intermediaries [33]. There are a number of consensuses adopted by cryptocurrencies and other applications; the most important are Proof-of-Work and Proof-of-Stake. Most of the consensuses are briefly explained as follows:

2.2.1. Proof-of-Work (PoW)

In this mechanism, all the nodes or miners in the network participate to solve a complex cryptographic puzzle for the verification of the transaction, and the node that is successful in validating the block is rewarded with the cryptocurrency of that network. In the case of Bitcoin, the successful miner will be incentivized with bitcoin, and in the Ethereum network, the miner will be awarded ether. In PoW, the participants holding at least 51% of the computational power can solve the cryptographic problem more swiftly and could have a monopoly over the network. Hence, PoW could be endangered if the participants hold at least 51% of the computational power of the network [34]. In addition, this mechanism is criticized for is high consumption of energy, such as in the case of Bitcoin [35].

2.2.2. Proof-of-Stake (PoS)

In PoS, only the miner selected from the network will be responsible for the validation of the data block. This mechanism has overcome the issue of high energy consumption seen in PoW [36]. The participant has to put some cryptocurrency at stake to become a candidate for the validating process, and the miner is selected randomly by the Blockchain network. The participant staking the highest amount of cryptocurrency has a high probability of becoming the miner. Only the selected participant becomes the miner and will validate the block in the network; by this mechanism, the validating process becomes fast, and the energy consumption of the whole process is much less compared to the PoW mechanism [37]. However, this mechanism possesses the issue that the wealthy participants in the network are more likely to be selected and this can become unjust to other participants.

2.2.3. Delegated Proof of Stake (DPoS)

Here, participants are chosen using DPoS via polling. The chosen delegates are also in charge of observing how the validators or miners in the network carry out the validation procedure. Each user of the Blockchain network casts a vote to choose a number of observers who will create blocks of Blockchain. In spite of choosing the candidates for witnessing, the network's users elect the candidates for decision-making on the protocols and parameters of the network, such as transaction fees, block size, and transactions per block. As a result, this algorithm is described as a "shareholder consensus voting technique" that promises fast transactions with little energy use [38].

2.2.4. Proof of Authority (PoAu)

Blocks in the Blockchain network may be created via PoAu by giving one or a small number of network users additional permissions or power. For instance, making modifications to the Blockchain would be the responsibility of the member owning a particular key. A polling system is used to bring new users into the network [39]. Simply said, it may be thought of as a modified version of PoS. The majority of authorized nodes must sign a block for it to be acknowledged, and network users place their faith in these nodes.

2.2.5. Proof of Byzantine Fault Tolerance (PBFT)

The Byzantine fault tolerance (BFT) algorithm originates from [40]. The majority of contemporary Blockchain systems that employ the voting-based consensus method use PBFT algorithms as a fundamental building component. In PBFT, a primary and secondary replica or duplicates are created where the primary duplicates are checked for accuracy and dynamism (the ability to respond in a specific amount of time) by the secondary counterparts, which may also switch to a new primary if the original one is compromised. Unlike public permission-less ledger systems, PBFT is better suited for usage in trusted contexts since each transaction is independently checked and signed by recognized validator nodes. Transactions are judged genuine, and the consensus is established when there are enough signatures gathered. The method requires at least two-thirds of the network to act honorably, and as the size of the network grows, communications latency may drastically increase, impacting both speed and scalability [41].

2.2.6. Proof of Capacity (PoC)

In Proof of Capacity (PoC), the validator nodes devote hard drive space to raise the likelihood that they will create the following block and obtain its reward. PoC can save a lot of energy and does not require the purchase of pricey ASIC (application-specific integrated circuit) equipment. The approach must, however, deal with problems comparable to the "nothing at stake dilemma" [38]. The Pylon-Core network based on the PoC consensus mechanism can process 7000 transactions per second [42].

3. Application of Blockchain in Power System

Blockchain technology can be a potential tool for managing increasing complexity in the electrical power grids due to intermittent renewable energy sources, DERs, and the concept of smart grids [3,43]. This section is mainly focused on the potential application of Blockchain technology in power grids such as in energy trading, power flow studies, electric vehicles, demand side management, grid automation, and security and privacy, as shown in Figure 6. Table 1 presents the categorization of the works of literature that are considered in the study under different domains of the electrical power system where Blockchain is finding useful and potential applications.

Figure 6. Application of Blockchain technology in electrical power system.

Table 1. Categorization of reviewed articles on different application domains in power systems.

Application Domain	References
Energy Trading	[13,44–53]
Power Flow Studies	[54–59]
Electric Vehicle	[37,60–69]
Demand Side Management	[47,70–73]
Grid Automation	[3,74–78]
Security and Privacy	[50,79–91]

3.1. Energy Trading

The increase in integration of DERs in the microgrids and community grids has enabled the new energy market, and P2P energy trading is gaining momentum. In P2P energy trading, the prosumers or the households in the community with excess or surplus electricity, can trade among the consumers. With the implementation of technology such as Blockchain in P2P energy trading, the seamless integration of the DERs is possible and Blockchain will offer immutable and transparent records of the transactions to all the participants in the networks [28]. Secure cryptography encryption provided by Blockchain technology also helps to maintain data security and integrity in the trading process [92].

Blockchain technology in energy trading will help to realize a decentralized trading network where the participants in the trading market can directly interact, negotiate and cooperate without the need for any central intermediaries [36,37]. Blockchain, along with the smart contracts, will help in automation and local energy markets, which are facilitated by localized P2P energy trading or distributed platforms, and can considerably boost energy self-production and self-consumption, also known as behind-the-meter activities, which can have an impact on revenues and tariffs [28]. The inherent characteristics of the Blockchain (security, privacy, and transparency) could be a potential technology to maintain trust among the participants in trading platforms without the intervention of central intermediaries. The elimination of a central authority in P2P trading will reduce the transaction speed and cost associated with it. In Blockchain information is open, and it facilitates transparency and security. Due to this, Blockchain has received a lot of interest lately from academics and the electrical industry, and it is being used in a variety of industries, including the energy trade [13]. Different studies conducted on Blockchain technology for energy trading are listed in Table 2. The Blockchain platform and published year are also listed in the Table. Similarly, Table 3 shows various companies implementing Blockchain technology for P2P energy trading.

Table 2. Summary of publications employing Blockchain technology for energy trading.

Study	Blockchain Platform	References
Case study on rural mini-grid of Baglung, where using Blockchain in electricity trading could solve the existing problem	-	[44]
A case study with 50 participants analyzing transaction volume and cost associated with energy trading	Ethereum	[13]
Review of Blockchain technology in the centralized energy trading market	-	[45]
The electricity trading market is based on a bidding system, which can be enhanced by incorporating Blockchain	-	[46]
Blockchain-based energy trading platform using Ethereum is proposed	Ethereum	[47]
Shows decentralized trading platform reduces the individual cost of electricity	Quorum	[48]
P2P energy trading platform based on Blockchain tested at a real Canadian microgrid	Hyperledger Fabric	[49]
A decentralized Blockchain-based electricity trading platform using an auction mechanism to trade available power among the prosumers	Ethereum	[50]
The Ethereum-based Blockchain platform is used for local electricity P2P trading market for 100 users	Ethereum	[51]
P2P trading based on a continuous double auction (CDA) mechanism is proposed	-	[52]
CDA mechanism is used to design a trading market	Ethereum	[53]

Table 3. Companies employing Blockchain technology for energy trading.

Company	Information	Blockchain Platform	Country of Operation	References
Green Power Exchange	Blockchain-based platform enabling simple P2P energy trading.	Ethereum	USA, China	[93]
Greeneum	Blockchain-based P2P energy trading platform utilizing smart contracts, AI and machine learning.	Ethereum	USA, Singapore	[94]
Electrify	Decentralized energy marketplace running on Blockchain and supports P2P trading.	Ethereum	USA, China, South Korea	[95]
WePower	Blockchain-based P2P energy trading platform using AI to estimate supply and demand.	Ethereum	Spain	[96]
Power Ledger	Blockchain-based P2P energy trading platform.	Ethereum	Australia	[97]
LO3 Energy (Exergy)	Localized energy marketplace employing Blockchain technology.	Private Blockchain	USA	[98]
Electron	Harness Blockchain technology in order to advance the energy market.	Ethereum	UK	[99]
SunContract	Blockchain-based decentralized P2P energy trading market.	Ethereum	Slovenia	[100]
Volt Markets	Blockchain-based P2P energy trading platform to streamline distribution, tracking and trading of energy.	Ethereum	USA	[101]

In the energy sector, Blockchain has a wide range of uses. The features of the Blockchain that makes it suitable for practical application in the energy sector, and especially in energy trading, are decentralization, accuracy, and anonymity. In [44], the authors have carried out a case study on a rural mini-grid of Baglung, Nepal. The author states the existing problem in the study, such as the lack of suitable and reliable communication mechanisms, a lack of data recording devices, and difficulty in maintaining security and transparency in electricity trading between the communities. The use of Blockchain technology in electricity trading in the mini-grid of Baglung could be a potential solution to address the problems existing there. A decentralized P2P energy trading platform, where the energy transactions are safeguarded, is practically realizable through Blockchain technology. In [45], the authors analyzed the Blockchain in the field of electricity and proposed a review for using Blockchain technology in centralized energy trading markets. A local electricity market, where the prosumers with the DERs could sell the available surplus energy to neighbors through a bidding system in the trading market, is proposed in [46], and it also analyzed the security of the trading platform and raises concerns related to confidentiality and safety. Similarly, a Blockchain-based energy trading platform on Ethereum is proposed in [47], where the system automatically, and in a timely way, balances the electricity supply and demand with substantial flexibility through the integration of DERs, and using the prosumers' electricity demand profile. The decentralized P2P trading platform could be effective in reducing the user's electricity cost, and also the overall cost of the community or an area where the trading platform is implemented. A transactive energy architecture based on Blockchain technology for the prosumers developed in [48] shows that the decentralized trading platform greatly reduces the individual cost of electricity by 77%, and the overall cost by 24%. Blockchain applications can make the energy transaction transparent, and this can also reduce electricity bills or the price of electricity.

In [49], the author proposed a P2P energy trading platform based on Blockchain technology and this has been tested at a real-world Canadian microgrid. Here, a Blockchain-based peer-to-peer energy trading platform has been developed to reduce the overall community peak demand and household electricity bills. A double auction method is utilized to clear the market and calculate the market clearing price (MCP), and the communities are made up of smart houses that submit offers for their available DERs for each discrete period of time during the day. The Blockchain technology is used as a transactive layer in P2P energy trading to eliminate the need for a central intermediary, protect the privacy of peers in-network, and to avoid single-point failure. A decentralized Blockchain-based energy trading platform, where the prosumers or the participants can trade the available electricity securely, efficiently, and transparently based on an auction mechanism, is proposed by [50]. The proposed framework utilized Blockchain technology along with smart contracts and smart meters. The function of the smart contract is to add automation to the trading process where it automates both the auction and the payment procedure. Whenever the prosumers have a surplus of available DERs, they can start a new auction and this surplus of available electricity is broadcasted into the Blockchain; then, other participants can participate in the trading platform and place their bids for the auction. Smart meters, on the other hand, are utilized to observe and review the electricity transaction, and they also aid in confirmation of the transaction.

A local electricity P2P trading market based on Blockchain technology is presented in [51], where an Ethereum-based Blockchain platform is utilized that works on a proof-of-concept consensus algorithm. The trading market is designed for one hundred users, and the trading platform is decentralized with the application of Blockchain and smart contracts. The smart contract will automate the auction mechanism, such as these smart contracts embedded inside the smart meters. The smart meters will automatically measure and predict the supply–demand trend of the user. As the data on the Blockchain is distributed among all the peers in the network; sometimes, this could also lead to privacy issues. To handle this, the designed framework would only measure and broadcast the participants' demand and production capacity to the other users.

The RENeW Nexus project funded by the Australian Government aims to use Blockchain technology and data analytics to enable P2P trading of energy and water. This project also uses an Ethereum-based Blockchain platform employing smart contracts. For this, the energy data is collected in real-time comprising energy import from the grid, energy export to the grid, energy generation from installed rooftop PV, and energy consumption in the household [13]. Here, the author has carried out a case study with 50 participants that aims to analyze the number of transactions and the transaction cost of energy trading using Blockchain technology. The results show that the cost of processing trading transactions is lower compared to the present coordinated costs, and also, energy can be traded more frequently than today's regulation would allow. The author also demonstrated how a second-layer approach might speed up transactions greatly and boost volume, while maintaining security and decentralization. This second-layer method employs a side-chain with a proof-of-stake consensus to record all off-chain transactions. In the side chain, the blocks are made up of a tree structure. When additional participants begin transacting with one another, the depth of the tree will increase. The side chains can scale with the least amount of trust by framing an off-chain transaction entry into a child of a side chain that is enforced by the parent chain. Only the Merkle root of the side-chain is recorded in order to add proof of the side-chain transactions to a public Blockchain ledger. Hence, the use of side-chain architecture can enhance the scalability of the Blockchain making the Blockchain scalable to larger applications. A scalable solution to the Blockchain application in electrical power systems, and especially in energy trading, could further be fostered by the use of new scalable solutions provided by Ethereum known as Layer 2 (L2) [102]. Furthermore, the transaction speed could be enhanced by the application of a decentralized Ethereum scaling platform named Polygon that allows up to 65,000 transactions per second [103]. In addition, the application of the Aztec network could significantly enhance the confidentiality of the Ethereum environment, thereby promising the security of Blockchain-based applications [104].

P2P trading based on a continuous double auction mechanism (CDA) is proposed in [52]. Here, the trading market is designed based on a continuous double auction mechanism where the results show that the P2P trading price and the quantity depend on the variation of the supply–demand ratio during each trading period. Although there is an absence of complex trading mechanisms and learning abilities, profits are able to be effectively and fairly distributed among the participants. This will encourage the participation of the consumers and prosumers in P2P trading and also increase the distributed energy generation. In this P2P trading model, the information network is organized in a centralized form whereas a decentralized system can be realized by employing Blockchain and smart contracts. A P2P electricity trading market based on Blockchain technology is also presented in [53], where a CDA mechanism is used to design the trading market.

Most of the literature, research works, and companies utilizing Blockchain technology for energy trading, and using Ethereum-based Blockchain platforms, implement smart contracts. Smart contracts are automated programs that execute a transaction on the Blockchain when the conditions defined on the smart contracts are met. Smart contracts add programmability and intelligence to the Blockchain. In P2P energy trading, each peer is equipped with smart meters accommodating the smart contract. The energy transfer between the peers on the distributed system would execute based on the smart contract [105]. Basically, in order to implement P2P energy trading, there must be smart contracts embedded in the smart meters. To design, code, deploy and execute the smart contracts, Ethereum Remix Integrated Development Environment (IDE) is one the platforms.

3.2. Power Flow Studies

The steady-state analysis of transmission or/and the distribution system network that computes the steady-state values of bus voltages and line powers from knowledge of generated power and loads at different nodes or buses of the power system network under study is known as a power flow or load flow study. Generally, power flow solutions compute differential equations and are very helpful for the planning and operation of the power system network. Under such a domain of electrical power engineering, it is not expected that the Blockchain would affect the power flow analysis, but it is fascinating that there are several pieces of literature utilizing Blockchain technology in the power flow study. Table 4 shows a list of publications that discuss the implementation of Blockchain technology for power flow studies.

Table 4. Summary of publications employing Blockchain technology for power flow studies.

Study	Blockchain Platform	References
A decentralized optimum power flow (OPF) for LV distribution networks and microgrids using Blockchain, smart contracts, and ADMM optimization	Private Ethereum	[54]
Implemented and experimented with the state-of-art Blockchain consensus algorithm for OPF	Ethereum	[55]
Introduced and distributed a Blockchain-based SCED algorithm	Consortium-Blockchain	[56]
Introduced a self-balancing differential evolution algorithm for ORPD in nine bus systems	Consortium-Blockchain	[57]
Use of Blockchain that eliminates the need for a central aggregator on the microgrid, and the scheduling of DERs was managed and fair payments were made	Ethereum	[58]
Blockchain-based proportional fairness control system where DERs are rewarded for grid service	Private Ethereum	[59]

The accelerated maturation and acquisition of DERs in a low voltage (LV) distribution network necessitate optimal management of these resources, which increases end-user flexibility while lowering electricity costs, provides critical services to the grid operator, and finally, aids in network supply–demand matching [106]. Typically, the management and operation of the DER are performed in the presence of a central authority [106,107]. To locally coordinate the DERs in the LV distribution network, the author presents a framework in [54], for decentralized Optimal Power Flow (OPF). The decentralized OPF is realized by the use of Blockchain (private Ethereum network), smart contracts, and the Alternating Direction Method of Multipliers (ADMM), where this proposed framework is suitable for the LV distribution network and microgrids comprising varieties of the DER. The system has been tested in a real-world scenario comprising 23 houses, a part of the East Harbor Prosumers Communities in Amsterdam, Netherlands. In [55], the author has implemented and experimentally analyzed a state-of-the-art Blockchain consensus algorithm for the OPF in integration with the ADMM. The consensus algorithm is called Proof of Optimal Power Flow (PoOPF) and it is successful in providing solutions to the OPF problems with a smaller number of iterations and less computational effort. The PoOPF will help to realize a trustless system where the independent power grid nodes on the network can be reached in unison with the OPF problem, and its effectiveness has been compared with well-established consensus algorithms. Its experimentation was carried out on the 39-bus New England transmission, IEEE-57, and IEEE-118 test buses. In [56], a distributed Blockchain-based SCED (security-constrained economic load dispatch) algorithm was introduced. Blockchain is employed in this concept to provide coordination among the participating members of the network and eliminates a coordinator, which implements a hierarchical SCED algorithm. The authors of [57] describe a self-balancing differential evolution algorithm for optimum reactive power dispatching (ORPD) in a nine-bus system and makes use of Blockchain technology from the standpoint of reactive power dispatch. This method is used to determine the power loss involved in each energy transaction. Through a case study, it was shown that the usage of Blockchain provides privacy protection and network transparency and is helpful for optimizing reactive power in a microgrid scenario.

In terms of confidence, confidentiality, dependability, and authenticity, Blockchain and smart contracts offer a solution for microgrid operation and are accomplished on the SCE 55-bus test system in a private Ethereum Blockchain network, where the authors coordinated the scheduling of DERs on a microgrid and ensured fair payments without the need for a central aggregator on the microgrid [58]. The study utilizes ADMM and the decentralized OPF model for the scheduling of the mixed loads on a distribution network. Blockchain is used to securely store the optimal schedules of the microgrids, and through smart contracts, the process is automated. Furthermore, the payments can be automated and secured without the requirement of any central intermediaries. On the other hand, microgrids consist of DERs, and their intermittent nature may result in grid instability causing voltage fluctuations; a solution to this instability is active power curtailment or reactive power adjustment [46,47]. In this context, a proportional fairness control strategy based on Blockchain technology is proposed in [59], where the DERs are incentivized for decreasing their output power, and these DERs are dynamically selected based on their control history. Here, a smart contract is used for automating the proportional fairness strategy, whereas the Blockchain helps to confidentially maintain a trustable distributed database. The study has also outlined the limits of using private Blockchain technology in the context of microgrids, which is restricted by high mining and communication costs. Blockchain is finding its potential application in power flow studies; although the research and study carried out in this domain is less, Blockchain could be a promising tool for creating a trustless, decentralized power grid.

3.3. Electric Vehicle Integrations

The increasing attention toward decarbonization and green energy technology has led to seamless integration of DERs in the microgrids. Distributed ledger technology such as Blockchain will be a promoting factor for the seamless integration of DERs. The studies that discussed the implementation of Blockchain technology for EV integrations are listed in Table 5. A Blockchain-based model for grid integration of various DERs, including the vehicle-to-grid network, is proposed in [60]. Blockchain technology may be used to enable smart charging for EVs [61]. A Blockchain energy trading platform for a vehicle-to-grid and vehicle-to-vehicle interface is discussed in [37], and this trading architecture is scalable to multiple nodes. The decentralized operation of the energy trading platform will improve power supply reliability [108]. A reliable, automated and secured EV charging platform based on Blockchain technology is presented in [62]; based on the cost and location, EVs may choose the best charging stations. By choosing the right charging station, Blockchain technology will contribute to enhancing the trustworthiness and transparency of the trade process.

Table 5. Summary of publications employing Blockchain technology for EV integration.

Study	Blockchain Platform	References
Blockchain-based energy trading platform for V2G and G2V interface	-	[37]
Proposed Blockchain-based models for grid integration of DERs and V2G	Consortium-Blockchain	[60]
Blockchain-based smart charging	Ethereum	[61]
Proposed reliable, automated, and secure EV charging platform based on Blockchain	Public Blockchain (Bitcoin, Ethereum)	[62]
Proposed P2P energy trading platform based on Blockchain for PHEVs	Lightweight Blockchain (modified)	[63]
Proposed adaptive Blockchain-based EV participation scheme	-	[64]
A Blockchain-based EV charging system where payments are completed in real-time	Consortium-Blockchain	[65]
Electricity trading platform where EVs can participate	Ethereum	[66]
Proposed energy trading platform where EV owners can sell extra energy to charging stations	Ethereum	[67]
An energy trading platform for EV and wind power generators using Blockchain technology and PSO optimization	Ethereum	[68]
A Blockchain-based rewarding system for EVs	Consortium-Blockchain	[69]

In [63], the authors proposed a P2P electricity trading platform for plug-in hybrid electric vehicles (PHEVs) using a consortium Blockchain that utilized a non-uniform double auction mechanism to specify the price and amount of an energy transaction. The trading platform maximizes social welfare and the use of Blockchain ensures trust and security. An adaptive Blockchain-based EV participation scheme is proposed in [64], where the major objective is to reduce EV charging costs and increase grid voltage stability. The analysis includes plans for the demand for EV charging and discharging to minimize the effects of using too much energy at the transformer substation level. In addition to considering the presence of mobile charging cars and attempting to ensure security and privacy for the operation, [65] proposes an optimal charging schedule architecture for EV charging based on a consortium Blockchain.

A Blockchain-based EV charging system is presented in [65], where payments are instantaneous in real-time and the information of the charging information could be addressed. Thus, the proposed system will enhance consumer satisfaction and also increase the confidentiality of the system with the introduction of Blockchain. In [66], the authors present an energy trading platform where EV owners may sell extra energy to the charging station. This method makes use of Blockchain technology to record transactions, and smart contracts are used to automate the trading process. Blockchain technology is used to build the charging payment mechanism in this case, ensuring privacy, trust, and transparency among EV customers. In [109], a Proof of Power consensus algorithm with smart contracts is deployed that will reduce the transactional delay associated with the mining or validation. This algorithm is useful in the case of Grid to Vehicle (G2V), and Vehicle to Grid (V2G) interface, and also in P2P energy trading. A Blockchain-based EV integration technique that is further improved by AI is suggested in [67] for smart grid power management. The outcome of the suggested technique demonstrates that EV integration offers private and open support in a smart grid setting. In a microgrid setting, energy trading might guarantee sustainable energy use.

The authors of [68] show an energy trading platform that integrates EVs and wind power into a microgrid using Blockchain technology and particle swarm optimization (PSO). To determine the best bid strategy for the transaction, the PSO approach is used. It is effective in resolving the issue of inadequate energy use in microgrids. The authors of [69] suggested a Blockchain-based incentive system for EVs, and it was discovered to be successful in using the energy in the microgrid and lowering the loads on the distribution system. Data on solar energy in California was gathered in order to replicate and verify this model.

3.4. Demand Side Management

During electricity supply shortage or high electricity prices, an automated demand response could be effective in load reduction and demand management [110–112]; this is discussed in [113,114]. Blockchain along with smart contracts will be an empowering technology for demand response programs. Smart contracts will be used to share the strategy behind the demand side management (DSM) program among the consumers, prosumers, and utilities. DSM will offer strategies for supply–demand balancing, increase the reliability of the system, and finally, effective and efficient utilization of the existing infrastructure [115].

A game theoretic model for the DSM enhanced by Blockchain technology is proposed in [70], where the model takes into consideration each person's demands, aids in using the variety of load profiles of the consumer sets, and accounts for supply constraints in the form of power interruptions. The model is effective in demonstrating how the peak-to-average ratio (PAR) and load valleys decrease, and finally, the smoothening of the load profile. In [47], smart contracts are used to store energy use and generation data from the prosumers' smart meter into the Blockchain, and smart contracts are also utilized to determine the prosumers' flexibility, along with any associated rewards or penalties and the rules for the supply–demand balance. Ethereum Blockchain was used, and the simulation was carried out by accounting 12 prosumers. An alliance formation algorithm-based P2P energy trading strategy presented in [71], demonstrates how well the suggested technique reduces peak demand. This scheme was put into action in a 12-consumer residential system.

Similarly, study [72] represents a decentralized price-based demand response that considers the willingness of the prosumer to provide flexibility to the grid service. This decentralized price-based demand response scheme could be fostered using Blockchain and smart contracts. For the secure participation of the prosumers in the demand response, [73] proposes a rewarding mechanism for the prosumers for motivating their confidential participation. As trust is of high value in these systems, along with privacy, security and transparency, implementing Blockchain technology along with smart contracts will foster the demand response programs and enhance its welfare. A summary of the studies that were conducted in this domain is listed in Table 6.

Table 6. Summary of publications employing Blockchain technology for DSM.

Study	Blockchain Platform	References
Propose a game-theoretic model for the DSM enhanced by Blockchain technology	Ethereum	[70]
Simulated supply–demand balance accounting for 12 prosumers using Ethereum Blockchain	Ethereum	[47]
Used an alliance formation algorithm-based P2P energy trading strategy for reducing peak demand	-	[71]
A decentralized price-based demand response program	-	[72]
A rewarding mechanism for secure participation of the prosumers in demand response	Bitcoin	[73]

3.5. Grid Automation

The traditional centralized power system grid architecture is being transformed into decentralized architecture where end consumers can now produce energy through DERs by which the consumers can now actively participate in providing the ancillary service to the grid to optimize and improve the performance of the grid [116]. The intermittent nature of these DERs makes voltage regulation a crucial service as the DERs could fluctuate the voltage profile of the grid [117]. In order to provide ancillary service to the grid and also to make the DERs participate in an energy trading model, the concept of a transactive energy system (TES) comes forward that enables the non-discriminatory participation of the DERs and provides perceptible and auditable interfaces [118]. The voltage compensation by DERs on the microgrids is achieved by the reactive power control, and the consumers with DERs can contribute to the voltage compensation by providing ancillary services by utilizing their own sets of generators and are incentivized for it [3]. Here, Blockchain is used for storing the transactional details and smart contracts automate the process and autonomously execute the monetary agreements. A Blockchain-based TES, where the participants in the active distribution system (ADN) will be incentivized for providing voltage regulation assistance, has been tested on a modified IEEE-33 bus system and on a real-world Canadian microgrid [91]. In the study, the use of the smart contract would implement the contract net protocol (CNP), thereby, automating the process of bidding, negotiation, auditing, penalizing, and validating the agent services. It clearly exhibits that the Blockchain-based platform will provide trust and auditability, whereas the smart contract will help to automate the process of offering grid voltage control in exchange for a reward.

The control and automation of the grid become increasingly important due to intensified consumer participation in the DERs' integration [119]. In addition, microgrids, along with the smart grids, are identified as a fair initiative towards the integrations of the DERs and it becomes essential to control and automate the processes related to the power and information flow across the grid [43]. A smart grid's characteristics include being fully autonomous, self-healing, and having autonomous fault management [49,50]. In this context, Blockchain can provide data integrity and confidentiality in these smart grids, and smart contracts can add automation, thus, helping to realize the smart grids in reality. In addition, this will help to transform the centralized grid architecture into a decentralized one. The authors of [76] demonstrated the potential of shared control for decentralized energy system management, where smart contracts are used for the control of two separately operated 33 kV distribution networks. The shared control elements are captured by the smart contract, which will legitimize decentralization and automate the process in the most dependable and safe way possible.

The advancement in ICT, along with the digitization of network infrastructures such as power grids and communication, and the development of the Internet of Things (IoT), has enabled automation; thereby, introducing the concept of the cyber-physical system (CPS) [56,57]. In order to provide a cohesive and intelligent grid service, CPS monitors the physical process and takes an appropriate response [120]. Resilience is a crucial component of CPS, and Blockchain technology holds promise for supplying the system with it, as well as security and decentralized operation. A Blockchain-based decentralized closed-loop CPS is demonstrated in [77], where data of the sensors are stored in Blockchain and the actuating action related to the CPS is automated though a smart contract. The study led to the formulation of a co-simulated framework interacting the MATLAB and Ethereum Blockchain, where the distributed frequency control of the microgrid is achieved.

Advanced Metering Infrastructure (AMI) enables two-way communication and is also aiding in grid automation [121]. In power system networks, the adoption of smart meters and ICT technology is on the rise [122]. The decentralized control and operation of the microgrids and energy systems could be effectively handled by Blockchain [28]. The automation aided by the Blockchain and smart contracts would be impactful in the decentralized operation of the energy trading platforms, green certifications, and grid management. The use of Blockchain and smart contracts in wholesale electricity trading eliminates the central intermediaries and the whole process of the energy transaction is automated and made confidential [28]. A crypto-trading platform whose main aim was to develop a Blockchain-based smart grid is presented in [75], where the smart grid helps in balancing the supply–demand and ultimately aids the energy trading market. In this trading platform, the participants can trade their excess available electricity in the trading market, and also monitor the status. The pivotal role of the Blockchain in this distributed electricity trading market is to serve as a distributed storage or directory to make the transaction transparent and to be utilized as a smart meter driving control system. In [78], the author proposes Blockchain as a tool for the transaction in the smart grid, and smart contracts will automate the trading process as the transaction is executed through smart contracts and the Blockchain network acts as a transaction validator. Here, the transaction is happening in the conventional centralized grid, and the generators could directly interact with the retail supplier or the consumer through the automated trading process where the smart contract replaces the central intermediaries. A similar application in automating the energy trading process has been discussed in aforementioned literatures in the energy trading section. A summary of some important studies that were conducted to automatize the power system via Blockchain technology are listed in Table 7.

Table 7. Summary of publications employing Blockchain technology for grid automation.

Study	Blockchain Platform	References
Rewarding DERs for providing ancillary services to contribute to voltage compensation	-	[3]
Transactive energy system based on Blockchain that provides an incentive for providing a voltage regulation service	Ethereum	[74]
A Blockchain-based smart grid that helps in balancing the supply–demand	Consortium-Blockchain	[75]
Demonstrated the potential of shared control for decentralized energy system management for two separately operated 33 kV distribution networks	Ethereum	[76]
Demonstrated Blockchain-based decentralized closed-loop CPS	Ethereum	[77]
Automated the process of bidding, negotiation, auditing and penalizing, and validating agent services using a smart contract	Ethereum	[78]

3.6. Security and Privacy

The advancement in the ICT and modern technology has led the electrical power system network to evolve into a smart system known as a smart grid. With this advancement, the energy market is also transforming into a decentralized market where a prosumer can sell energy to their neighbor. However, energy trading in the smart grid poses its own sets of challenges related to the deceit, and fallacious data administration, of the system, which may result in high price points, and faithless transactions in the trading market. A summary of some important publications that used Blockchain for security purposes is listed in Table 8.

Table 8. Summary of publications employing Blockchain technology for security and protection.

Study	Blockchain Platform	References
Foster resiliency of the smart grid using Blockchain technology	Ethereum	[79]
Aggregates data effectively and efficiently using Blockchain technology for privacy preservation	Private Blockchain	[80]
Use of Blockchain and a smart contract for fostering the resiliency of the smart grid	Ethereum	[81]
Blockchain is used to effectively and efficiently aggregate data from electricity consumers	Ethereum	[82]
Decentralized trading platform where data of prosumers, consumers and smart meters are stored and broadcasted to the Blockchain	Ethereum	[50]
Presents a safe energy trading algorithm for a two-layer interconnected microgrid	Ethereum	[83]
A CDA-based electrical transaction model for microgrids	Consortium-Blockchain	[84]
A software-defined networking (SDN)-based Blockchain-based energy transaction model ensuring safe energy transactions	-	[85]
Present security and privacy of an EV trading platform utilizing Blockchain and Byzantine consensus algorithm	-	[86]
A-PoL is proposed to protect energy trading participants' anonymity	-	[87]
Blockchain-based solution for paying power bills	Ethereum	[88,89]
Build load scheduling methods on the Blockchain, which is safe and reliable	Hyperledger Iroha Blockchain	[90]
A Blockchain-based autonomous power dispatch methodology where data are securely aggregated	Ethereum	[91]

In [79], the author makes use of Blockchain technology along with smart contracts in order to foster the resiliency of the smart grid. Here, the author also explored the secure transactive energy application. Blockchain applications could be crucial in assuring security concerns in the energy trading market. Smart meters acquire data and information about the electricity usage of a consumer that can be utilized by the utilities for various proposes [123]. The electricity usage profile of the consumer could be used maliciously, thereby posing threat and security issues. In [80], the authors grouped electricity consumers for the purpose of collecting their data, and utilized Blockchain technology to effectively and efficiently aggregate data while preserving user privacy. The information in the Blockchain is transparent, and was distributed among all the users or peers in the network. This could also lead to some privacy issues in an electricity trading platform based on Blockchain technology. In [50], where a decentralized Blockchain-based electricity trading platform was proposed, all the data of the prosumers, consumers, and smart meters was stored and broadcasted to the Blockchain. If the data stored and broadcasted into the Blockchain are not encrypted or coded, then the data may be compromised. This can be a serious issue related to transparency and privacy. Such issues can be eliminated by establishing a trading platform where the users' identity is not disclosed by using encrypted information flow and multiple signatures [81].

Blockchain technology offers a safe environment for energy transactions that upholds participant confidence and privacy in the energy trading industry. In [83], the authors present a safe energy trading algorithm for a two-layer, interconnected microgrid based on Blockchain technology. The solution successfully facilitates reliable energy trading in a microgrid setting and enhances the platform's security and privacy. Wireless media was used to complete and record a Blockchain-based secured energy transaction model that was suggested in [82]. The proposed approach will function more effectively by automating the transaction with the aid of a smart contract. The authors of [84] present a CDA-based electrical transaction model for microgrids that makes use of consortium Blockchain technology. The results show that this approach, which is a privacy protection method, may be applied to direct electrical transactions in a microgrid environment. A software-defined networking (SDN)-based Blockchain-based energy transaction model is presented for the energy internet in [85], which ensures a safe energy transaction by protecting the participants' anonymity on distributed energy trading platforms.

In terms of energy trading security, [86] presents an EV-based energy trading system that utilizes Blockchain technology and the Byzantine consensus algorithm to protect the security and privacy of the EV trading platform. Testing the system on the IEEE-33 test bus demonstrates the viability of this strategy. A Blockchain-based anonymous position certificate (A-PoL) technique that protects energy trading participants' anonymity is proposed in [87]. Blockchain technology promotes security, decentralized trade, and privacy protection for prosumers and consumers.

Using smart meters and Blockchain technology, tamper-proof invoicing of electricity with high levels of confidentiality could deploy [124]. In [88], the authors proposed a Blockchain-based solution for paying power bills that offers great confidentially and protects against electrical energy fraud problems. The use of smart contracts will assist to automate the procedure and obliterate fraudulent activity. A similar system is also proposed in [89]. The aforementioned literature [62] on EV charging platforms based on Blockchain technology is also aimed at the privacy preservation of the users where the information related to the geography of the user is not exposed and also the users on the Blockchain are anonymous. In [90], a load scheduling method built on the Hyperledger Iroha Blockchain is described as being safe and reliable. This system, which is based on real-time pricing for many customers, guarantees safe, reliable energy transfer. PSO is employed for autonomous power dispatch in [91], which proposes a Blockchain-based secured data aggregation methodology. The PBFT consensus method serves as the model's foundation.

4. Discussion and the Way Forward

A new energy management system based on energy trading amongst prosumers is created as a result of the shift of the power market from a centralized to a decentralized structure [32]. Because of this, peer-to-peer distributed energy trading may be implemented, enabling prosumers in the distribution system to trade energy [33]. Auditability, privacy, and security are three main challenges with traditional peer-to-peer energy trading networks. It is difficult to verify the accuracy of energy transfers across peers in a decentralized P2P system without access to the peers' history records. Although if peers' past records are made public, serious privacy problems arise, which would drastically limit peer involvement. Using a trusted, central intermediary to validate all peer transactions is a potential method; however, this introduces a single point of failure and makes the system unsafe. Implementing Blockchain-based P2P energy trade might solve some of the privacy, security, and transparency issues that the P2P-based energy trading paradigm has. However, Blockchain is still in its infancy stage of development and there is still work to be done before Blockchain-based energy trading can be widely used in practical applications [125]. The issues and challenges related to the integration of Blockchain in power system application are shown in Figure 7. Nevertheless, Blockchain appears to be a viable technology for building effective, fraud-proof, secure, and transparent decentralized platforms for applications in the electrical power system.

The reliability of the main grid is impacted negatively and scalability issues are raised by the use of Blockchain and smart contracts to establish large-scale renewable and other DER integration [43]. This is because more nodes are becoming interconnected, which calls for a substantial amount of processing power to manage the correspondingly growing volume of transactions brought on by wholesale and peer-to-peer energy trading. One significant flaw in Blockchain technology is scalability. The number of processing resources required rises as the number of blocks and transactions on the Blockchain rises, and transaction speed may eventually slow down. However, recent advancements in the Ethereum ecosystem, such as the Polygon and Aztec networks, could be utilized to address the problem of scalability and confidentiality. Research under the paradigm of scalability and security in Blockchain technology is of prominent interest due to the increasing size and complexity of modern systems. Smart contracts now serve a very basic purpose. They are rule-based programs that are capable of doing a variety of tasks according to accepted logic. A smart contract's value will improve dramatically if machine learning (ML) and artificial intelligence (AI) are combined with it. ML and AI could make the smart contract more adaptable, and can create and execute smart contracts by providing crucial analysis. Furthermore, a smart contract could also be able to learn for itself, make adjustments, and operate in a semi-autonomous way [13]. The main issue with a decentralized platform is security. Due to the immutability and transparency of the Blockchain, which are two of its primary qualities, the application might provide security. Blockchain technology has not yet been thoroughly investigated and is still in its early stages of development. Researchers and organizations thinking about implementing Blockchain technology must comprehend its fundamentals. Blockchain might not be appropriate for all applications, and it will not necessarily solve every issue. In the context of this, Figure 8 presents a flowchart that was adapted from [126] to assist in deciding whether or not a Blockchain may be required for an application.

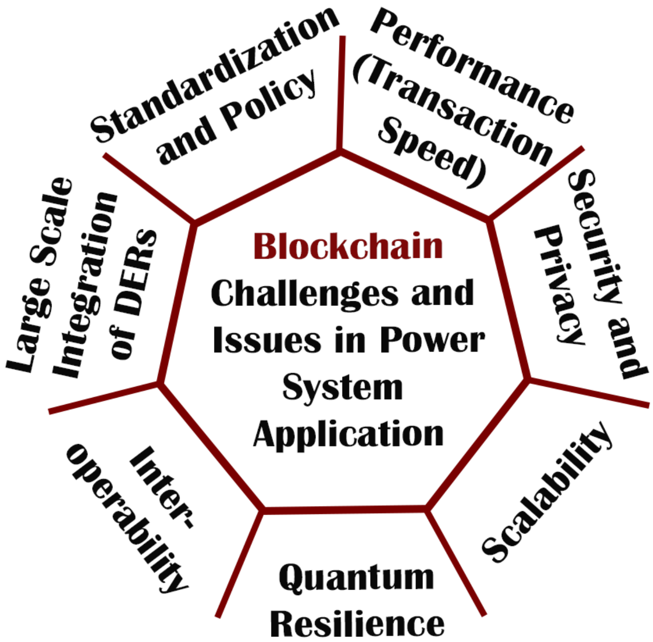

Figure 7. Blockchain challenges and issues in power system application.

Blockchains potentially have security vulnerabilities, such as the loss of private-public key pairs or a 51 percent vulnerability attack. The exposure of the public–private key might result in the pattern of transactions being revealed, which could then disclose the habits and behaviors of the market players. As a result, the trading market's participants' or prosumers' identity is compromised. Additionally, the smart contract used to automate the trading process may have flaws that encourage dishonest users or peers to manipulate the system [34]. Blockchain technology may be impacted in the future by developments in computing technology. Blockchain technology will be significantly impacted by the potential breakage of the Blockchain's encryption and cryptography by quantum computing. Hyper Ledger Fabric is one example of a private or consortium Blockchain that may be used to address these problems and concerns. Additionally, providing momentary session keys and public-key encryption with timestamps may be able to completely eliminate any security risks to the Blockchain and smart contract. At present, STARK (Scalable Transparent Argument of Knowledge) a Layer 2 Blockchain protocol build over Ethereum ensures post-quantum security [127]. Hence, the application of STARK could eliminate the threat of quantum computing to Blockchain-based applications.

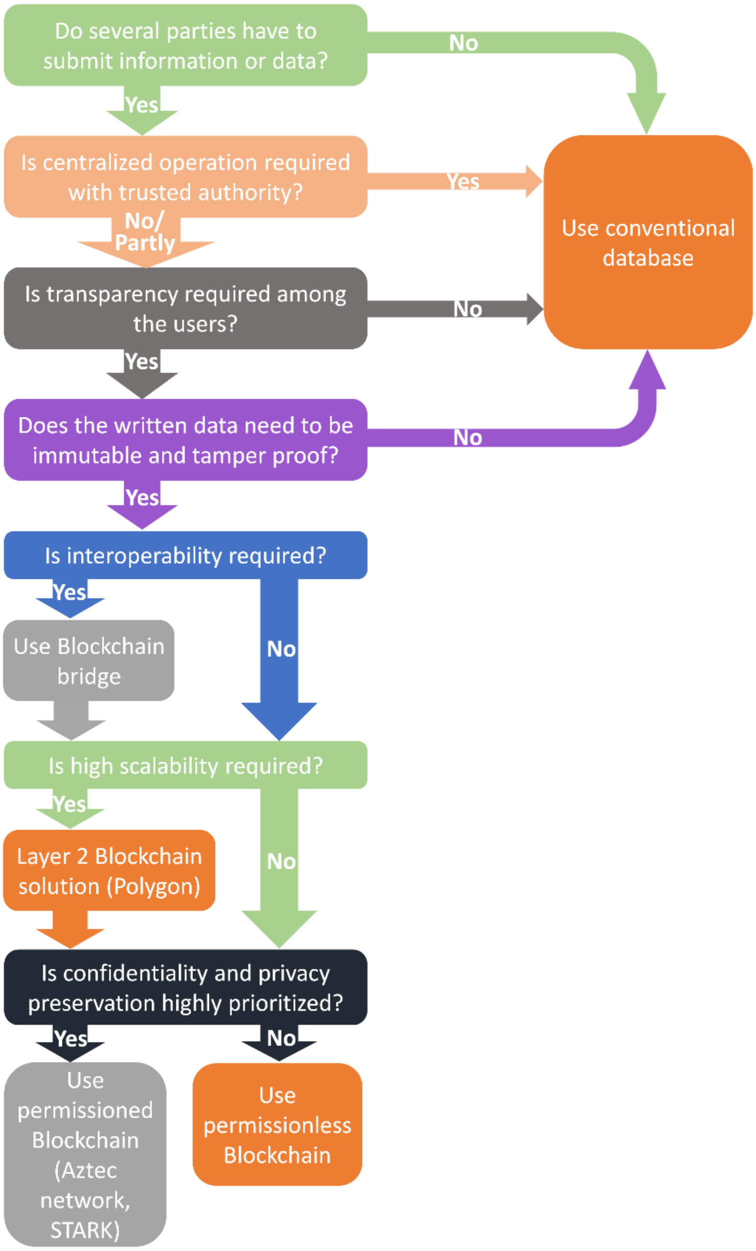

Figure 8. Flow diagram to evaluate the suitability of Blockchain application in electrical power system.

The increasing electrical power system network is facing new challenges as a result of the expansion of distributed power generation. Further research into effective management systems and methods is, therefore, necessary. The majority of research has concentrated mostly on transaction transparency, but one of the main concerns with the adoption of Blockchain technology is the protection of users' privacy in decentralized systems built on the Blockchain, such as energy trading networks [128]. At present, research in user privacy is focused on the use of zero-knowledge proof and zero-knowledge cryptography for transactions [127]. The Aztec network is one of the solutions for providing enhanced privacy protection and the Mina protocol is another example that stands out for its lightweight design, privacy-preservation, and easy validation [104,129]. Blockchain networks have a high installation cost in order to achieve a high degree of data integrity, eliminate central authority, and increase security [28,128]. Due to implementation challenges in a wide range of applications and the fact that Blockchain is still in its early stages of development, there is a risk that it might malfunction. There is also a significant possibility of security flaws before the system is developed, which might lead to negative publicity and a delay in market acceptability. Smart contracts are used with smart meters to take advantage of automation. In order to apply Blockchain technology to the electrical power grid, smart meters need to be built with significant computational capabilities. The use of Blockchain technology could encourage customer engagement in the regional power market [130]. However, the administrative, legal, policy, nation or area, and application of using Blockchain should be investigated, which substantially challenges the adoption and acceptance of Blockchain technology. Standardization is also necessary for Blockchain and smart contracts. The interoperability of this technology will be hindered by a lack of standards. Blockchain bridges have been created in recent years to offer the best options for interoperability across various kinds of Blockchain networks. These bridges can connect contracts across platforms and transport assets. They are already commercially accessible, such as the Binance bridge and Avalanche bridge [131]. However, the Blockchain bridge is in its early stage of development and possesses issues related to censorship, theft, and smart contract risks [132].

5. Conclusions

Blockchain stands to be a fundamentally promising technology for decentralized power system applications, and it has gained great interest and application in recent years. Various companies and industries are investing in Blockchain technology, especially in energy trading based on Ethereum implementing the smart contract. Blockchain is still in its nascent stage of development and possesses various challenges related to scalability, decentralization, and security that need to be tackled. The issues related to scalability, decentralization, and security could be addressed with the current advancements in Blockchain technology and incorporated into its application in electrical power systems, making the modern and future electrical system more robust and resilient. In addition, its potential use should be viewed from the region or country's viewpoint. Nevertheless, the use of Blockchain along with smart contracts will ensure trust, security, and transparency in decentralized power system applications, and finally, make a decentralized power system and power market a realization.

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