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Review

Impact of Blockchain Technology on Smart Grids

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Abstract: Energy systems are transforming due to the incorporation of multiple distributed energy resources, such as renewable energy and battery storage systems. This transformation has triggered a need to shift power distribution from a low efficiency centralized model with high coordination costs to a decentralized distribution system comprising smart grids. Researchers have discovered a number of uses for blockchain technology in the energy sector because of its decentralized structure and possibility for safe transactions. In order to pinpoint current trends and important research directions in this area, this article thoroughly examines the effects of blockchain technology on smart grids and distributed energy resources. The aim of this paper is also to identify research gaps and future research initiatives in the area of blockchain-based energy distribution. To do this, 92 research publications were subjected to a comprehensive literature review based on predetermined criteria. Transactive Energy, Electric Vehicle Integration, Privacy and Security, and Demand Response, together with some other relatively fresh and unexplored topics, were, therefore, highlighted as four major focal areas of blockchain energy research. We have also drawn attention to the gaps in the research that has already been done and the constraints imposed by present systems that must be removed before blockchain technology can be widely used.

Keywords: smart grid; blockchain; distributed energy resources; DER; impact; systematic literature review; SLR; literature review; review

Citation: Khan, H.; Masood, T. Impact of Blockchain Technology on Smart Grids. *Energies* **2022**, *15*, 7189. https://doi.org/10.3390/en15197189

Received: 6 July 2022
Accepted: 16 September 2022
Published: 29 September 2022

1. Introduction

Power systems are changing and growing at a pace never previously witnessed, and they are becoming increasingly crucial to society and the economy [1]. The goal of decarbonizing the planet as a result of environmental and sustainability measures is one of the key forces behind this development [2]. The European Union has set for itself aggressive targets to produce 32% of all energy from renewable resources by 2030 and reach the 100% renewable mark by 2050 [3]. While these initiatives are a positive step towards a sustainable and environmentally friendly power system, they bring with them many challenges that the current infrastructure is not ready to meet. The integration of various distributed energy resources (DERs) at various points in the transmission system is one of the largest modifications to the power distribution networks. The resources might range in form, size, purpose, and integration point, and each one presents a unique set of difficulties for system operators.

The addition of a multitude of small and large power systems in the grid is slowly transforming the power industry from a centralized to a decentralized system (Figure 1) marked by multiple buyers and sellers of energy [4,5]. As shown in Figure 1a, currently, most energy distribution networks consist of centralized producers supplying electricity to both commercial and residential consumers with distributed and ancillary generators providing a small portion of energy to balance the grid as needed. However, as more distributed energy resources are incorporated in the grid (Figure 1b), the distribution model is expected to eventually transform to a fully decentralized model in the form of multiple microgrids consisting of prosumers and consumers transacting power within the microgrid (Figure 1c). This decentralization results in many challenges, such as grid congestion, coordination, grid balancing and unpredictability, etc. [6] and has given rise to the concepts such as microgrids, virtual power plants, demand response and local energy markets, Internet of Energy (IoE) and smart metering etc. [7–10]. However, even with many of these new concepts, recent literature has suggested that a central entity cannot efficiently coordinate a decentralized power system, and hence, a decentralized mechanism is needed for future energy systems [11].

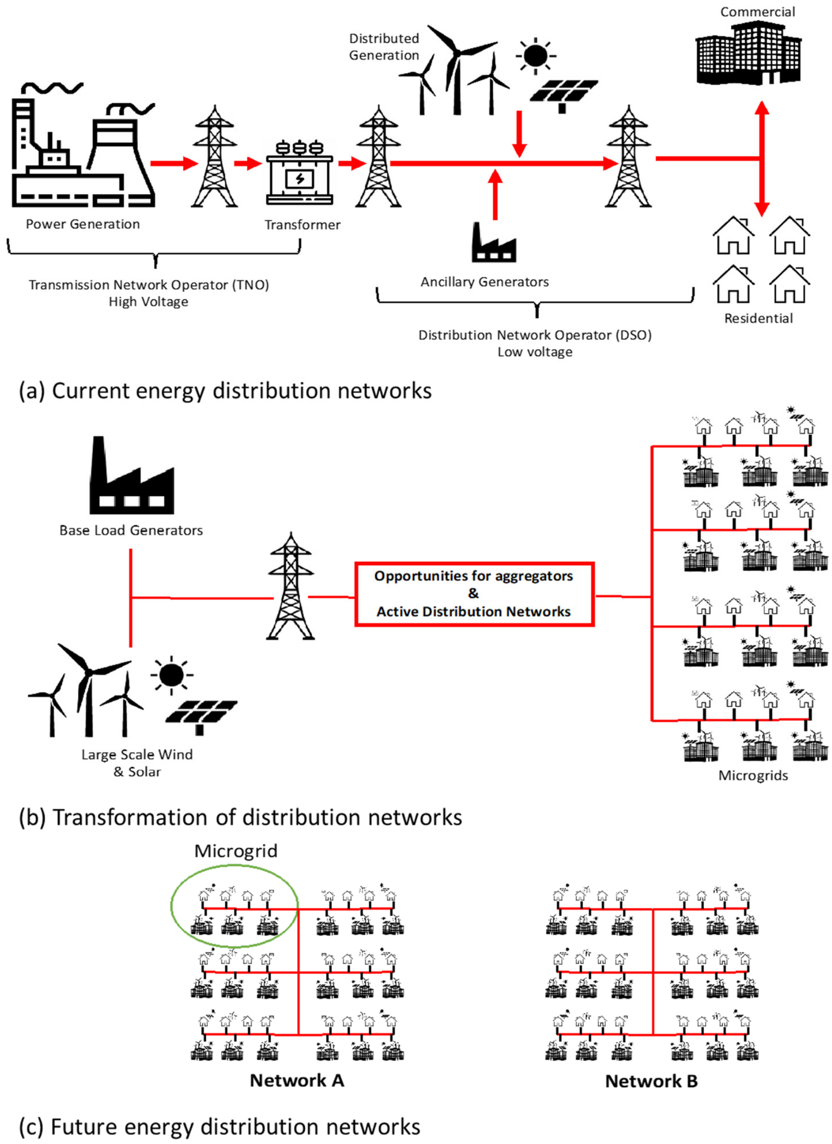

Figure 1. Transformation of the distribution network.

Ever since its advent in 2008, blockchain has been labeled as one of the most revolutionary technologies and researchers have been developing novel ways of applying this technology to different fields [12]. One such application has been in the energy sector [12]. Blockchain technology eliminates the requirement for a reliable third party in the exchange of energy by providing a decentralized and secure platform for data sharing and managing complexity [13]. By enabling peer-to-peer trading, electric car involvement in the smart grid, and small-scale prosumer collective trading in energy markets, the new market can be opened up to opportunities [14–17].

This article's aim is to provide a thorough analysis of the current status of energy blockchain research and identify key research areas in this field. This article also analyzes the present research gaps and potential uses of blockchain technology in the energy industry. This article's remaining sections are organized as follows. The context and rationale for this systematic review are given in Section 2. The review's methodology is explained in Section 3. The present state of research is examined in Section 4. The research gaps and opportunities for future research are covered in Section 5. The review's conclusions and contributions are given in Section 6.

2. Background and Motivation

With the rapid growth and inclusion of DERs in the power grid, scientists and engineers are developing novel methods to meet the challenges that these DERs bring. An analysis of the various review articles (Table 2) published in relation to DERs shows that the Intermittency and Uncertainty of DERs are key issues in this field, especially with renewable resources such as wind and solar [18]. This uncertainty creates a coordination and grid balancing problem for the distribution system operator (DSO) that needs to balance the uncertain demand and supply to ensure acceptable power quality. In a centralized system, the large power plant and supportive ancillary services are under the control of the DSO, who can adjust the supply with changing demand [19]. However, in a decentralized system, the DSO not only has to coordinate between a high number of consumers, producers and prosumers, but it must also incorporate the uncertainty and intermittency of these DERs.

Another rising challenge regarding the power grid coordination is the increasing number of electric vehicles (EVs) in the grid. With the rising demand of EVs, there is a growing need for a well-coordinated and secure charging infrastructure that maintains the privacy of the end user and at the same time reduces the burden on the grid by optimal coordination in EV charging times [20]. Simultaneously, electric vehicles also provide an opportunity to overcome the challenges of grid balancing and power quality issues [9]. In addition to load balancing and power curve flattening, due to their batteries' capacity to ramp up and down, EVs may offer auxiliary services such as frequency and voltage regulation [21]. However, coordination between hundreds and thousands of electric vehicles to balance the grid is a challenging and highly expensive task for any centralized entity [9].

As mentioned in the previous section, recent literature has shown that decentralization of power grids is a viable solution to the challenges posed by DERs, and blockchain technology has emerged as a frontrunner in decentralizing energy markets. In the past few years, there has been a sharp rise in works related to energy blockchains and many articles and books have been published in this regard. In addition, many conferences have been dedicated to discussing the different ways blockchain can be leveraged to improve future power systems. To this sense, we think a thorough analysis of previous research on blockchain technology is necessary to synthesize concepts, identify research gaps, and suggest potential future lines of inquiry.

As shown in Table 1, various review articles have been written in this regard. However, most of these reviews are not systematic, and hence, bound to have gaps. Out of all the research articles, there are three that are systematic; however, ref. [22] systematically reviews real-world initiatives but does not consider theoretical and experimental works and [23] exclusively takes into account start-ups and practical research initiatives—the technique for choosing the assessed works is not disclosed. The study that most closely resembles the current one is [13], which carefully evaluates the state of the art but only takes into account 16 journal papers and mostly ignores conference pieces. In computer science and related fields, conference articles are often highly valued among researchers [24], and in a fast moving research area such as blockchain, many novel ideas and research avenues are presented in conferences. For this reason, we believe a review without considering conference articles is incomplete.

Table 1. Analysis of reviews of blockchain applications for the energy industry.

Review Articles	Systematic Review Search Terms	Focus Area	Review Article Gaps	Future Opportunities
Miglani et al. (2020) [9]	Not systematic	Internet of Energy	None identified	• Development of rules and regulation • Network lag • Energy consumption • Incorporating energy losses
M. L. Di Silvestre et al. (2020) [17]	Not systematic	Power Systems	None identified	• Experimentation • Security and resilience • Consensus algorithms and scalability
z. Zeng et al. (2020) [10]	Not systematic	Information Security	• Energy markets not discussed • Peer 2 Peer trading not discussed • EV scheduling mechanisms not discussed	None Presented
P. 'Donovan and D.T.J. O'Sullivan (2019) [22]	Systematic AND (Review OR Mapping OR Study OR Survey) AND Energy AND Blockchain	Real World Initiatives	• Only real-world initiatives considered • Theoretical and Experimental initiatives not considered • Research Articles not considered	None Presented
H. Khajeh eet al. (2019) [19]	Not systematic	Flexibility Trading	• Articles primary focus is not blockchain technology	None Presented
E. Svetecet al. (2019) [25]	Not systematic	Renewable Energy Sources	• Focus on EU and Croatian markets • Primarily Focused on Microgrids • Important areas such as security and privacy not considered	None Presented
E. Erturk et al. (2019) [13]	Blockchain AND Energy	Smart Energy	• Only 16 articles reviewed Conference articles not considered	• Economic feasibility • Transaction costs
T. Alladi et al. (2019) [26]	Not systematic	Smart Grid	None identified	• Scalability and cost • Contingency plan for forking and fragmentation • Self-adjusting power systems • Forecasting grid requirements
M. Andoni et al. (2018) [23]	Search string not provided	Start-ups and Pilot Projects	• Only projects and startups systematically reviewed • Methodology not provided	• Consensus mechanism • Development of lot platforms • Security and resilience • Development cost and infrastructure • Regulation and standardisation

Table 1. *Cont.*

Review Articles	Systematic Review Search Terms	Focus Area	Review Article Gaps	Future Opportunities
S. Kushch and F. P. Castrillo (2017) [27]	Not systematic	Renewable Energy Sources	• Blockchain technology is not the primary focus of the article	None Presented
Mattos, D.M.F. et al. (2021) [28]	Not systematic	Smart Contracts	• Only focuses on security and reliability • Not systematic	• Scalability • Security • Performance
Guo, Y. et al. (2022) [29]	Not systematic	Blockchain for smart grid	• Methodology not provided	• Reliability and Safety • Scalability • Privacy • Security • Performance

Table 2. Analysis of review articles summarizing the challenges of integrating distributed energy resources in the electric grid.

Author & Year	Area of Focus	Intermittency and Uncertainty	Grid Balancing	Issues Identified Power Quality	Coordination	Integration of EVs
S. K. Rathor and D. Saxena, 2020 [17]	Energy Management systems	• Uncertainty quantification method • Uncertainty handling methods	X	• Power quality management systems • Loss minimisation and reliability	• Communication • Aggregator and demand side coordination • TSO/DSO coordination	• EV behaviours • EV nonlinear loads
J. A. P. Lopes et al., 2019 [1]	Smart Grids	• Time varying nature of RES	• Decentralisation to balance uncertain demand and supply	• Voltage and frequency control	• Coordination for P2P trading	• Dynamic distribution integration in the power grid
L. Lind, R. Cossent, J. P. Chaves-Ávila, and T. Gómez San Román, 2019 [2]	Transmission and Distribution systems	• TSO needs to be more flexibility to incorporate DER uncertainty • DSO will have to perform active grid management	• Integrating balancing markets	• Power quality is controlled by DSO • DSO must procure flexibility to provide congestion management services	• Coordination schemes between DSO and TSO • Coordination schemes for flexibility procurement	X
E. M. Carlini, R. Schroeder, J. M. Birkebaek, and F. Massaro, 2019 [21]	Impacts of Renewable energy resources	• Need for flexibility to counter uncertainty	• Balancing markets • Balancing procurement methods	• Capacity management systems	• Coordination between TSO's • Regional security coordination	X
A. K. Singh and S.K. Parida, 2017 [5]	Deregulated Electricity Market	• Reliability and risk evaluation techniques • Capacity markets	X	• Challenges on system operators to maintain quality • Quality standards	X	X

Finally, we think our evaluation will be helpful for future works in blockchain applications for smart grids and DERs because there has not been a thorough systematic review and because it is crucial to combine research to identify existing gaps and future directions.

3. Methodology

To get a comprehensive grasp of the work done in this field, identify research gaps, and open doors for future research, a systematic literature review was conducted. The methodology used for this study is based on the ideas of [30,31] and has been modified from the literature review of [32]. Figure 2 shows the overall methodology adapted for this review. The documents shown in each step are the sum of the documents from both selected databases. Additionally, many other relevant articles were found through citation tracking and manual searches. Lastly, while a quality criterion has been established, some articles that do not meet this criterion have also been selected if they present a novel idea or findings that the authors determined relevant to the current work.

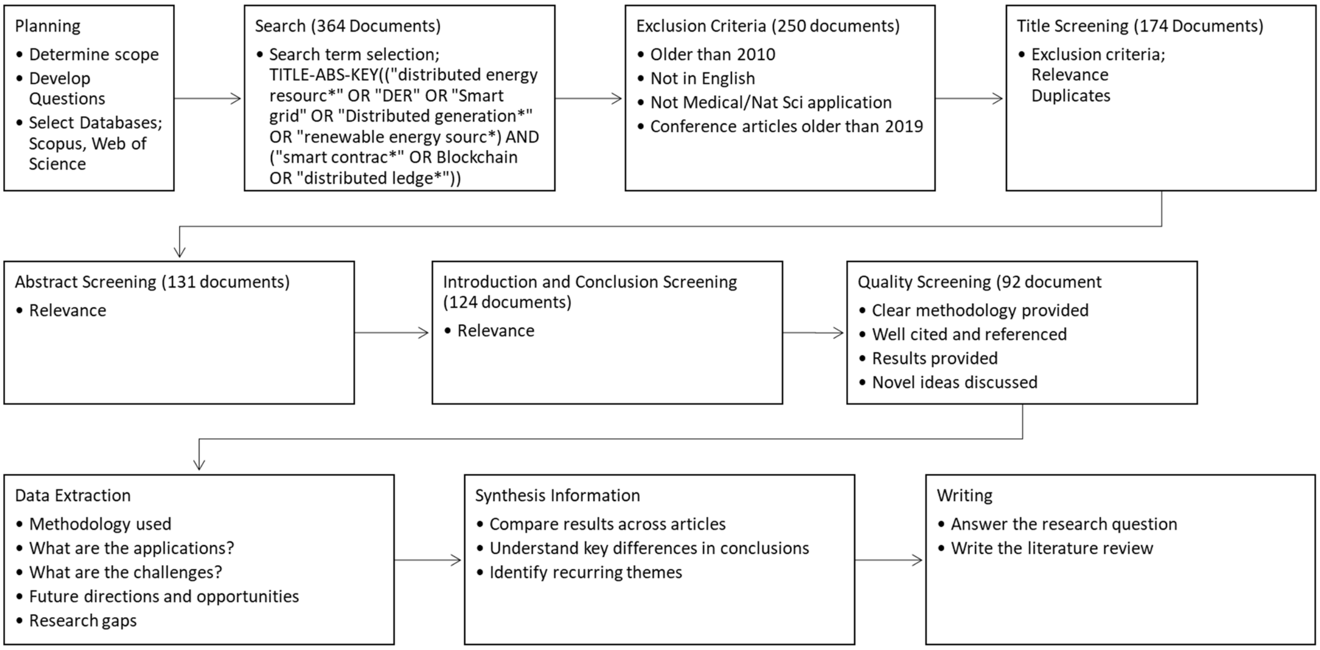

Figure 2. The methodology followed to conduct this systematic literature review.

3.1. Review Questions

This work's main aim is to provide an answer to the research question, 'What is the current research status of blockchain technology in relation to smart grids?'. To achieve this aim, four review questions were developed to guide this work and carry out a focused review.

(1) What are the main areas where blockchain technology is being used in smart grids?

The objective of this question is to examine the major research areas and the areas of concentration within those areas. Additionally, this question will help identify the major organizations and researchers involved in this field.

(2) What research methodologies have been used to blockchain-enabled smart grids?

The purpose of this question is to identify the typical research methodology used in this field and to classify the various validation techniques used in the evaluated publications. This will help other researchers create their own research techniques and choose the best research instruments.

(3) What challenges do smart grids have while using blockchain technology?

This inquiry seeks to classify the difficulties currently encountered in the implementation of blockchain technology in the energy industry as well as the difficulties encountered by the suggested solutions in the evaluated works.

(4) What are the research gaps that need to be filled before blockchain technology can be used in smart grids practically?

This inquiry tries to pinpoint the gaps in the available knowledge and the solutions put forth that prevent the effective application of blockchain technology in smart grids.

(5) What may the future of blockchain technology research in the smart grids look like?

This inquiry seeks to identify potential future lines of investigation in this field that might significantly advance the development of blockchain-enabled microgrids.

3.1.1. Search Methods

A systematic literature review was conducted to answer the guiding questions described previously. The methodology is shown in Figure 2 and the two platforms used to complete this search were:

- Scopus;
- Web of Science.

In order to conduct the search, the following search string was used in both databases:

TITLE-ABS-KEY ((“distributed energy resourc” OR “DER” OR “smart grid” OR “distributed generation*” OR “renewable energy sourc*”) AND (“smart contrac*” OR blockchain OR “distributed Ledge*”))*

The search string was defined to find literature in the intersecting fields of blockchain technology and distributed energy resources. For a comprehensive search, other terms such as “smart grid”, “distributed generation”, and “Renewable energy resources” were included in the search, as these are often used interchangeably for DERs. However, because the creation of smart contracts is central to many blockchain applications in the energy industry, the phrases “smart contract” and “distributed ledger” were also included. The literature covering distributed ledger technology was also pertinent to our investigation because blockchain is a sort of distributed ledger. See Appendix A for visualizations of the literature based on a social network analysis.

3.1.2. Screening Method

The screening method employed to select the articles for review has been shown in Figure 2. As mentioned in the previous section, in addition to journal articles, conference articles have also been considered in this review, as these often contain novel research and are well received in the computer science and related fields. However, only conference articles from the last 2 years have been considered, as it has been assumed that the important findings presented in conference articles older than 2019 would have been formalized in journal articles by April 2020.

Next, articles that were not in English and those in irrelevant fields, such as medicine, biology, astronomy, etc., were excluded from the results.

These results were then scanned for relevance in four steps. In the first step, the title was read to understand relevance, in the second step, the abstract was read, and in the third step, the introduction and conclusion of each article was read. Using this technique, literature relevant to the research topic was identified and reviewed and the information was stored in a spreadsheet for further analysis. A representative partial of the spreadsheet is shown in Table 3, and the information collected is summarized in the subsequent sections.

Table 3. A representative partial of the spread sheet used to analyze the information collected during the systematic literature review of 124 research articles.

Author	Focus	Key Takeaways	Methodology	Challenges	Proposed Solution	Future Opportunities	Research Gaps
Cutsem, Ho Dac, Boudou	Demand Response	Renewable energy consumption increases through cooperation	Case Study	Create cooperation between buildings to achieve a common goal	Smart contracts	incorporating prediction uncertain for market model	What if nodes (customers) don't respond to market or provide their schedule?
			Smart contract Ethereum	Centralised: solutions for energy management	Day ahead planning		
		Communities overall cost of energy decreases	Program Python	Issues of privacy	Real time tracking	Cost of smart contract execution	
				Local solution required	incentivising and penalising		
Agung, Handyani	Blockchain network to manage transactions		Ethereum used Examples shown Mobile application developed	How to ensure generators supply after consumers pay	Smartcontracts for energy transactions	Ethereum only does 15 transactions per second	Consumers have to pay from before
				Who will validate the transactions?	Government plants can reduce price if needed	No promotion of clean energy	Market is regulated by the government
						Proof of work is resource intensive	No case study system not verified
Vavalis, Foti	Energy markets	To fulfill market step time demand the block creation time must be several magnitudes lower than the auction time (5 times)	Case Study	Decentralisation	Uniform price double auction mechanism	Effect of block generation on market competition	does not incorporate uncertainty of DERs
			Ethereum	Enabling DERs			does not include day ahead markets
		Installing computation modules on smart computing devices can lower block size	GridLab-D for power grid simulation	Enabling smart grids	Base on blockchain for real time energy markets	Create a specialised blockchain	What about quality?
			Consortium P2P network				

3.2. Review of Methodologies Used

Blockchain is a rapidly developing technology, with new kinds of blockchains being created on a regular basis that are suitable for various uses. It is crucial to comprehend the many blockchains employed in smart grid research as well as the advantages and disadvantages of each of these technologies. The majority of the work on blockchain applications in smart grids makes use of the Ethereum blockchain network with a proof-of-work consensus algorithm [33], as described in [22] (see Table 4). Ethereum is a public blockchain network that is open source and has functionality for smart contracts, which is most likely why it is used most frequently rather than because it is the most suited.

Ethereum is widely used, making it easier for researchers to collaborate. The Proof of Work (PoW) method is widely described in the literature as unscalable and resource intensive [9]; however, most research articles use this method because this is the default method of most blockchain networks, including Ethereum. Many researchers use Proof of Stake (PoS), delegated PoS (DPoS), Proof of Authority (PoA), and Byzantine Fault tolerance as the consensus procedures to provide more scalable possibilities [34–36]. Proof of Stake has been shown by many researchers to be a more practical alternative to the problems faced by Proof of Work; however, it can be inefficient, and to solve that problem, researchers have used DPoS instead [32]. The other most frequently used blockchain is the Hyperledger Fabric [37,38]. Lastly, Khorasany et al. [39] proposed a novel consensus mechanism, 'Anonymous Proof of Location (A-PoL)', to increase privacy while validating the location of the user to eliminate bad actors.

Table 4. Comparison of various blockchain technologies and consensus mechanism used in energy applications from the articles reviewed.

Comparison of Commonly Used Blockchain Technologies and Consensus Algorithms				
Entity	Name	Research Articles	Strengths	Weaknesses
Blockchain Technology	Ethereum	MengelKamp et al. (2018) [8] Vavalis and Foti (2019) [40] Afzal et al. (2020) [41]	• Most widely available • Opensource • Executable code (Solidity) • Created for smart contracts	• Primarily uses Proof of Work which is not scalable • Slow rate of transactions
	Bitcoin	Armani et al. (2019) [42]	• Most widely used cryptocurrency • Highly liquid currency	• Long transaction time • Built solely for transactions • Proof of Work consensus which isn't scalable
	Hyperledger Fabric	Goranovicet al. (2019) [43] Patsonakis et al. (2019) [44]	• Framework for permissioned networks hence more secure • Audit functionality • Modular architecture allowing customisation	• Permissioned network, hence, not fully decentralised • New framework with limited proofs of application • Consensus algorithm depends on the trustworthiness of each member of the network
Consensus Mechanism	Proof of Work (PoW)	Hua and Sun (2010) [33] Jindal et al. (2019) [45]	• Most commonly used • More secure than other existing methods	• Not scalable • Vulnerable to 51% attack • High associated costs
	Proof of Authority (PoA)	Nurgaliev et al. (2019) [36] Ahl et al. (2019) [46]	• Fastest transaction time compared to PoS and PoW • Very low computational requirements	• Security depends on validator • Tends towards centralisation
	Proof of Stake (PoS)	Fan and Zhang (2019) [47] Niu and Zhang (2019) [34]	• Energy efficient and lower associated costs • More scalable as compared to PoW	• High level of complication • Difficult to secure • Allows multiple chain mining
	Practical Byzantine Fault Tolerance (pBFT)	Sheikh et al. (2020) [35] Su et al. (2019) [48]	• Transaction finality • More energy efficient than PoW	• Vulnerable to Sybil attacks • Difficult to scale due to the involvement of every node in each transaction

The research projects reviewed mostly use private and consortium-based blockchain networks; however, some articles also use public blockchain networks due to its advantages of decentralization. While public blockchains are completely decentralized and users are hidden behind a layer of cryptography, all the transactions are public. By studying multiple transactions, it may be possible to match user keys with different users, creating a huge privacy and security risk. Additionally, public blockchains are extremely energy intensive, as each transaction must be broadcasted to each member of the network. Private blockchains reduce the computational load and ensure that only trusted parties can join the network; however, this makes the blockchain more centralized. Consortium networks are a hybrid of public and private networks and are particularly suited for energy trading purposes [49]. Consortium blockchain further reduces the computational stress, as only a few trusted nodes are given read/write permissions; however, since the nodes can be chosen in a decentralized manner, there is no consolidation of power.

The reviewed research articles have primarily used case studies as a mean of testing the developed mechanisms and systems [40,50]. Additionally, some articles use data from various smart grids and utility companies to simulate the performance on actual grids [51,52]. Many projects focused on smart contracts have used solidity as the language to write the contracts [53], whereas GridLab-D has been used frequently to simulate smart grids [40].

4. State of the Art

4.1. Current Areas of Research

In this section, different areas of research are broadly divided into four primary categories:

(1) *Transactive energy*—which includes local markets, P2P trading, and smart contract methodologies;
(2) *Electric Vehicle Integration*—which includes EV charging mechanisms and Vehicle to Grid trading;
(3) *Privacy and Security*—works focused on ensuring privacy and security of blockchain-based smart grids and trading mechanisms;
(4) *Demand Response*—blockchain-based smart contracts and mechanisms made for adjusting electricity demand to match the supply.

The last category in this section is titled miscellaneous and discusses various novel and unexplored areas of blockchain energy applications, with only a few articles related to them. For each focus area, the current state of the art is discussed as well as the challenges identified in each article and the attempts to solve those. It should be noted that the different areas have overlapping focus, for example, transactive energy research also focuses on security and privacy; however, these have been distinguished based on their primary focus.

4.2. Challenges

In this section, the challenges that blockchain technology has been used to solve are reviewed and discussed in the literature. Since the literature reviewed can broadly be divided into four categories, the challenges have also been divided in the same manner, as shown in Table 5.

Table 5. Challenges for the application of energy blockchain initiatives.

Transactive Energy	EV Integration	Privacy & Security	Demand Response
Incorporation and Coordination of DERs [40]	Privacy of EV charging and user personal data [48,54]	Secure and reliable P2P Energy Trading [55,56]	Decentralisation of Demand response systems [57]
Match Demand and Supply [33,58]	Hackers may be able to compromise EVs through charging stations [54]	End user identification through energy consumption patterns [59]	Development of pricing mechanisms [57]
Reduce Cost of DER incorporation [60]	EV charging schedules to reduce grid stress [16]	Consolidation of power in private and consortium based blockchain networks [21]	Matching variable supply with uncertain demand [57]
Reduce energy wastage [57,61,62]	V2G capabilities to use EVs as batteries for grid stability [21]	Methods to trace transaction and identify malicious behaviour [63]	Maximise local RES consumption [64]

Table 5. *Cont.*

Transactive Energy	EV Integration	Privacy & Security	Demand Response
Energy Market for small scale prosumers [33]	Untracebility and Unlinkability between EV and charger [65]	Scalable consensus mechanisms [66]	Increasing consumer coordination [64]
Market clearing and pricing mechanisms [67]	Incentivising EVs to participate in the grid as DERs [68]	Blockchain memory issues [34]	Privacy of consumers involved in demand response schemes [69]
Reliable payment methods [17]	Most EVs do not possess V2G capabilities [70]	System lag due to complexity of calculations [47]	Development of trust between consumers and aggregators [71]

In addition to the above-mentioned challenges discussed in the literature, various challenges were identified that could not be classified into the above four categories. An area for large potential of blockchain applications is billing and metering, as shown in [37]. A micro level view of energy consumption patterns is required for efficient service, while there is also a need to preserve user privacy [37]. Additionally, as there is a shift towards automation, there is a need to develop remote metering and billing mechanisms that ensure trust for all parties [72,73]. Another area for research mentioned in [74] is power quality. It has been found that most electric breakdowns occur not because of power generators, but due to issues in the powerlines, such as congestion, breakdowns, and demand supply mismatch [75], which requires high levels of coordination between various entities of a smart grid.

While most of the literature is focused on the technical side of energy blockchain initiatives, ref. [76] highlighted a severe lack of regulation, which limits P2P trading in most countries. It is argued that without appropriate regulations and approvals, any trading mechanisms created will not be practical.

Edge computing has been frequently mentioned as a solution to the latency problems faced by energy blockchain initiatives [60,63]. However, as discussed in [77], edge computing faces many security issues which need to be addressed. Carbon credit auditing and tracking of clean energy production and transfer also presents many challenges [78]. Batch consensus and Join-and-Exit mechanisms have been presented in [79] as a potential solution to the latency problem.

Blockchain technology has found many applications in the energy sector; however, there is a major concern regarding the amount of bandwidth required to implement this technology on a large scale [80]. Comprehensive studies need to be carried out to understand the bandwidth requirement of energy blockchain applications. Furthermore, studies need to be conducted to determine the hardware and communication technology needed to successfully implement blockchain networks in the energy sector [43].

4.3. Transactive Energy

The most often mentioned field of study is transactive energy (TE). Out of the 124 articles initially selected, at least 44 articles were related to transactive energy. TE is defined in [81] as:

> "Techniques for managing the generation, consumption, or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints."

Using this definition, we review the different research avenues within TE.

The primary focus of all TE research is to develop P2P or P2G energy trading mechanisms to allow secure blockchain-based trading using smart contracts and smart grid infrastructure. The articles discussed assume that each consumer/prosumer has a smart meter installed that is tamper proof and is connected to the network to send received receipts. A comprehensive market mechanism is proposed in [50], which shows that a 61.5%

increase is seen in profits for a decentralized microgrid with P2P trading compared to the existing centralized mechanism. The article utilizes a three-layer mechanism comprising a grid layer (or physical layer), an information layer, and a business layer (or blockchain layer) to carry out P2P trading (see Figure 3).

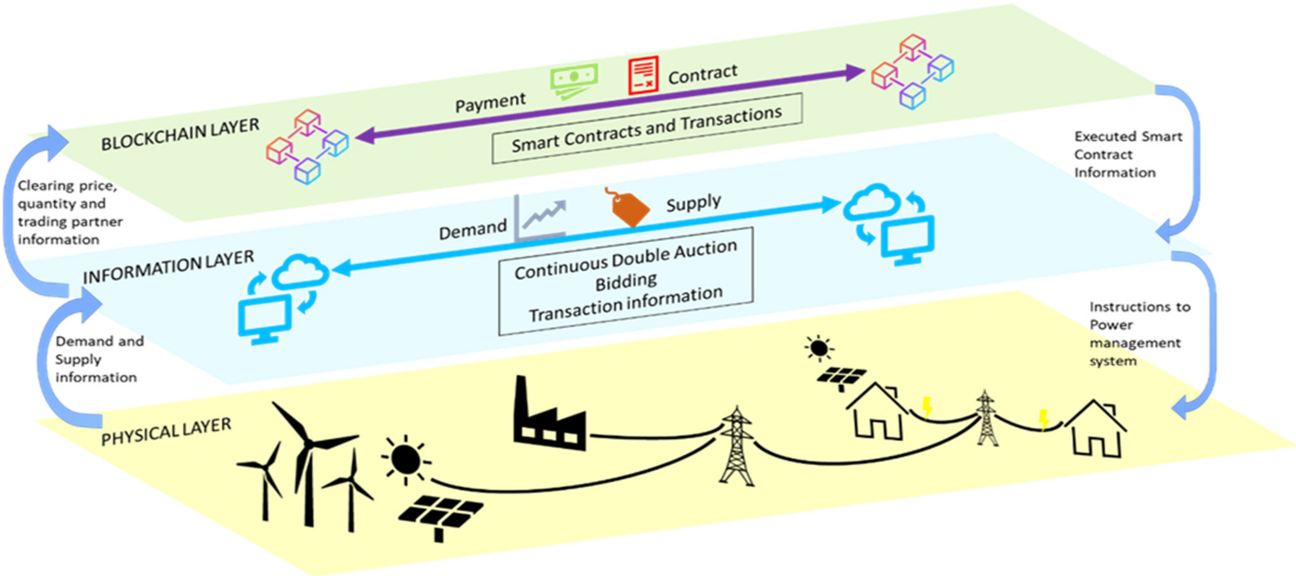

Figure 3. A type of blockchain-based decentralized energy distribution system. It can be seen how various areas of research discussed in this article fit together to form a blockchain-based energy distribution system.

A Monte Carlo simulation predicts future supply while applying time pressure on buyers and sellers to reach a deal. In addition, the trading mechanism allows each buyer to pursue their own business goals of minimizing costs or losses, maximizing renewable energy consumption, etc. Lastly, the mechanism overcomes the problem of grid congestion by applying penalties to regulate demand. Ref. [82] developed a multiagent system that allows prosumers to form coalitions to negotiate wholesale electricity prices and [83] promoted prosumer coordination to reduce energy prices from the grid. Additionally, ref. [82] used a blockchain-based transaction settlement mechanism. Ref. [60] utilized an adaptive aggressive strategy to reach clearing price in continuous double auction market. The article shows that an adaptive aggressive strategy that discloses market information after each auction round is an appropriate and efficient method for transactive energy. On the other hand, ref. [40] used a uniform price double auction mechanism to clear the market. The article shows that the block creation time must be several orders of magnitude lower than the auction time to fulfil the market step time demand. Alternatively, ref. [84] suggested creating smart contracts using price from a central grid to eliminate the burden of price clearing and auction from the blockchain network.

Another direction for research is the coordination between different microgrids. Ref. [58] showed that networked microgrids (islanded self-sustaining grids) are more efficient and financially feasible than independent microgrids; moreover, they can sell excess energy at times of overproduction and purchase cheaper energy at times of under-production. Additionally, ref. [58] suggested the use of a master controller that allows for trade between DSO and Microgrids; particularly, the DSO has been tasked with providing ancillary services and bridging the gap between intermittent supply and varying demand. Ref. [53] utilized a private blockchain network to allow for price negotiation and focus on developing a reliable payment mechanism. In this proposal, a “Commit to Pay” certificate is introduced that a buy generates upon agreeing to purchase electricity. The certificate ensures that the buyers funds are locked and cannot be used until the energy is transferred or the certificate expires. This overcomes the challenge of ensuring a trustless payment mechanism. Ref. [85] proposed a three-layer model that allows inter- and intra-VPP energy trading for optimized grid balancing, overcoming the challenge of a singular central authority to balance the grid.

The main conditions for a local energy market (LEM) based on blockchain are outlined in [14]. According to the study, a successful implementation requires a clear value proposition that makes use of already-existing grid components. A crucial aspect in the article is also the necessity of V2G interoperability in an LEM for future deployment success; activities centered on V2G are described in the following sections.

As mentioned in the challenges, scalability is a major challenge for blockchain-based energy trading. Ref. [86] showed that system latency increases with the number of concurrent clients and the size of transmission for each transaction depends on the number of generators taking part. Ref. [87] addressed the latency issue by creating a bi-layer micro-micro and micro to macro platform consisting of a main consortium blockchain and independent public side chains to transact within a microgrid. Conversely, ref. [33] coupled carbon and energy markets by providing monetary compensation to promote renewable energy and rewards users for reducing carbon consumption. However, as suggested in [88], this area needs more work to reduce the carbon footprint of blockchain technologies, as the massive carbon footprint of blockchain mining may have a net negative effect on the renewable energy markets. Ref. [89] suggested dividing consumers and distributors into light and full nodes to reduce the infrastructure burden on the consumers and increase the authority of the distributors, resulting in lower transactional overheads, and [90] showed that permissioned IBFT 2.0 blockchain can reduce latency significantly when compared to Ethereum HFRAFT and KAFKA.

4.4. Electric Vehicle Integration

Electric vehicles were the second most discussed area of blockchain energy research. While most TE articles also incorporated the use of electric vehicles, the articles discussed in this section were primarily focused on the use of electric vehicles as DERs in V2G trading or various charging mechanisms or coordination schemes for electric vehicles to ensure privacy and security while reducing the burden on the grid.

In the literature, several EV charging systems have been proposed. Ref. [48] suggested a DBFT consensus-based permissioned blockchain-based EV charging system. A central operator uses the optimal contract theory to fulfil the EV needs while maximizing operator utility. However, this system may face scalability problems due to its lack of decentralization. Ref. [70] overcame these challenges by creating SMERCOIN, a type of cryptocurrency purposefully created for EV charging. EVs are incentivized to charge on a renewable energy-friendly schedule in two ways: a monetary incentive, where payments are made through cryptocurrency, and a non-monetary incentive, by giving priority to EVs that follow the schedule. Through a 15-month trial, it has been shown that EV participation increased significantly and the cost for aggregators was reduced using this methodology.

To solve the problem of the impact on the battery of an EV, ref. [16] proposed a mechanism that takes into account the properties (such as the capacity, charging rate, etc.) of each EV to accommodate its involvement in the smart grid. The suggested approach also makes use of an adaptive iceberg order execution algorithm to enhance the charging and discharging schedules, and it demonstrates that this results in reduced computing costs compared to previous Ethereum-based platforms. In addition to various charging mechanisms, researchers have also proposed various privacy and security solutions for EV charging using blockchain technology. Ref. [91] suggested a system where prosumers can directly sell energy to EV via smart contracts; however, the location of the EV is not disclosed to the prosumer using cryptography. Conversely, ref. [92] proposed a smart contract-based charging system for remote EV chargers on highways as well as community charging for microgrids. Ref. [65] solved the challenge of privacy in V2G systems by creating an aggregator based anonymous rewarding scheme that rewards EV for taking part in the smart grid. However, by creating an unlinkable and untraceable smart contract, challenges arise in the event of dispute resolution and transaction tracing. Ref. [93] proposed a mutual authentication scheme where only a central authority has the EV information, whereas the supplier and EV transact anonymously. Ref. [68] provided another scheme for hybrid EV participation in the smart grid based on double auction where the local aggregators perform the role of auctioneers with the aim to maximize social welfare. However, the consortium-based system utilizes the proof of work method which is not scalable. As an alternative, ref. [94] built a V2G trading system based on the Ethereum network using a Proof of Benefit consensus protocol. When compared to previous V2G trading techniques based on Ethereum, the scheme demonstrates that the proof of benefit protocol provides a more stable grid with less volatility. Refs. [60,65] solved another key challenge of V2G trading by utilizing edge computing to reduce system latency. Ref. [95] showed that the probability of successfully creating a block increased by 124.6% by using edge computing to carry out computation closer to the end user.

4.5. Privacy and Security

One of the primary aims of implementing a blockchain-based system for DERs is to ensure end user privacy and security. As a result, these themes are the subject of much investigation. The papers in this area cover how to create private and secure energy blockchain applications.

To understand the potential threats posed by cyberattacks, ref. [58] created a test bed to simulate cyberattacks on transactive energy systems based on blockchain. This test bed can be used by other researchers to test proposed schemes and compare across different blockchain-based TE systems. Furthermore, to mitigate malicious behavior, ref. [58] suggested imposing fines on malicious parties to discourage dishonest behavior. Similarly, ref. [96] suggested fining malicious behavior; however, the proposed system is centralized and the utility operator has control of the data. In this regard, blockchain is used for transparency to allow the user to track his consumption and payments in an immutable database increasing trust and reliability. Similarly, ref. [97] suggested a central trusted authority with oversight on automated smart contracts in a V2G network, where the authority can track any malicious behavior; however, a compromised central authority would put all users at risk.

As suggested in [51,56], to combat cyberattacks, DeepCoin can be used, which is a blockchain and deep learning-based TE system that uses blockchain for smart contracts to trade energy and deep learning for security and intrusion detection. The algorithm monitors the network to learn and adapt from cyberattacks to build its security. Due to the considerable danger posed by suspicious nodes that regularly disconnect from the network, ref. [66] created a new consensus protocol called hyper delegated proof of randomness that takes the dependability of a node into account when selecting it to create a block. For further elimination of false data injection (FDI), ref. [98] proposed a bi-layer model where energy controllers also communicate over the blockchain, and to test this, ref. [99] proposed an FDIA simulation model for smart grids.

Alternatively, ref. [100] utilized a noise-based system to reduce adversarial impacts of data mining attacks. The system allows individual sellers to create multiple accounts through which energy can be traded, which ensures that energy trends for a user are never revealed. Additionally, the article proposes a black box containing a token bank, which can be considered a layer of privacy between the buyer and seller. Both the buyers and sellers can deal directly with the token bank to redeem or purchase tokens to buy or sell energy.

A similar privacy-protecting mechanism utilizing multiple accounts was suggested in [59]; however, this system uses a randomizing approach to select the aggregator node to publish the data to improve security. The node with a bid price closest to the final chosen price of energy is selected. While this may be random at the start, over time, malicious nodes may be able to use machine learning approaches to predetermine market clearing prices and increase the change of being selected as the aggregator nodes. Additionally, it has been shown that this sort of method carries high computational burden.

In order to guarantee user privacy, ref. [55] created the energy trading platform PriWatt, which is based on the cryptocurrency BitCoin. This platform provides an anonymous messaging service for buyers and sellers to negotiate prices without being identified; additionally, this system uses a multi-signature scheme, where n out of t nodes must verify the transaction for it to be approved. Finally, to ensure user privacy while maintaining the security of the blockchain network, ref. [101] proposed a permissioned blockchain trading network with three layers: Edge Nodes, Super Nodes, and smart contract layers. The proposed system overcomes the issue of user privacy in permissioned blockchain networks (since the permission granting nodes may know the identity of the other nodes) by utilizing Covert Channel Authorization (CCA), which masks the identity of the Edge Node from the authorizing Super Node.

4.6. Demand Response

The US Department of Energy has officially defined demand response as:

> "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." [102]

In order to perform demand side response smoothly and in a coordinated manner, many demand side aggregators have come to business, which adjust demands of the end user within the limits established by the user. In this way, a demand aggregator capitalizes on the incentives provided to adjust electricity demand in response to rising prices and it shares this profit with the end user in return for his cooperation.

Hence, by its very nature, demand side management requires the use of real-time contracts, data recording, storage of secure and private information, and an efficient payment mechanism [103]. For this reason, blockchain technology has been proposed as an appropriate platform for the demand side management, whether it is a demand side aggregator or a decentralized system without a trusted third party.

In [41], a community-based demand side management strategy was employed. To schedule appliances in a community depending on the cost of power, a game-theoretic mathematical model was developed, while blockchain technology was employed to protect user privacy. It has been demonstrated that this method minimizes the community's overall energy expenses as well as individual prices, while also improving the energy consumption profile.

Researchers employed cooperative energy management across a group of smart buildings in [64] to efficiently control demand with the goal of maximizing local renewable energy usage and lowering energy expenditures. Blockchain-based smart contracts incentivize following the demand schedule and penalize overconsumption, while maintaining consumer privacy. Ref. [69] took a slightly different approach to load balancing and instead of real-time monitoring; as suggested in [64], the consumption data of a user are aggregated over a month and forwarded to the utility company, which rewards or penalizes the consumer if they have maintained the pre-planned consumption schedule. By aggregating data for a month, ref. [69] solved the challenge of privacy for end users, whose daily activities might be exposed in real-time monitoring, leading to security risks. Ref. [104] proposed a dual pricing strategy for aggregators to use internal and external microgrid prices to optimize clearing price and energy demand.

The challenge of aggregator consumer trust was addressed in [71], where a method to measure the reputation of aggregator/consumer was developed based on various criteria. Using this reputation, the consumers and aggregators were matched, and it was found that this produced a higher interoperability success rate when compared to other methods. Additionally, the developed demand response mechanism provides more incentives to entities with better reputations, which encourages all entities to actively participate to increase their reputations.

4.7. Miscellaneous Areas of Application

In this section, we discuss various areas of blockchain energy initiatives that do not fit in the aforementioned focus areas. We found few research articles with a focus on the below mentioned issues, and hence, these may be considered uncharted territories in terms of literature.

In [37], the researchers created a smart metering system based on blockchain to address the issue of user privacy by allowing users to store information locally until it is needed by the DSO. This eliminates the issue of real-time information leaking. Similarly, ref. [72] presented a conceptual framework for remote metering based on blockchain that allows for the secure processing and transfer of high volumes of energy data.

The optimum power flow model was used by [74] to plan local power distribution while taking into account network limits and employing blockchain technology to ensure the system's security in order to address the issues with energy quality. To do this, an algorithm was devised using a general form method known as the Alternating Direction Method of Multipliers (ADMM). The framework was tested using actual data from a neighborhood in Amsterdam, The Netherlands. A well-developed physical microgrid and information system, defined market rules, pricing mechanisms, microgrid objectives, an energy management trading system, and regulations are just a few of the seven objectives that [76] outlined as being necessary to successfully execute a microgrid solution.

Ref. [77] created an efficient key management system to safeguard edge computing infrastructure as well as an anonymous authentication and key agreement protocol to assure the security of edge computing systems. Ref. [105] created a system to decentralize equipment safety diagnosis in order to streamline and automate troubleshooting. To ensure payment and responsibility, a smart contract was established between the consumer and the maintenance provider.

In [78], a method of tracking renewable energy production was developed, and carbon credits were tokenized to make them easy to trade, and due to blockchains properties, accounting and double counting issues were overcome. Ref. [80] showed that blockchain-based energy trading platforms require 10 times more bandwidth than existing smart meter systems. Furthermore, it was shown that DSL and fiberoptic-based communication infrastructure provide the necessary bandwidth, speed, range, and cost to be used for this purpose, whereas PLC-based systems are limited to only 10 participants.

5. Research Gaps and Suggested Future Directions

Following a thorough analysis of the current state of the art and the challenges associated with using blockchain technology in the energy industry, we have determined six main areas of focus for future research.

5.1. Research Gap 1: Incorporating Demand and Supply Forecasts in Energy Markets to Understand the Impact of Uncertainty on Market Mechanisms

Almost all the work reviewed related on TE and LEMs based on blockchain made an overarching assumption regarding the DER supply and consumer demand and did not consider it in the pricing, auction, or trading stages of the framework. For example, the energy auctions in [67] assumed perfect supply forecasts have been made during the auction stage of the trade. Supply forecasts will influence the behavior of both the consumers and producers during trades [106]. For example, if a consumer purchases a certain amount of energy and is unable to receive it the next day and must depend on the expensive centralized grid energy available, they may alter their trading pattern to purchase energy from multiple prosumers or purchase excess energy. Similarly, sudden increases in energy demand can cause grid imbalance, energy shortage, and increase the energy prices. Prosumers may alter their trading patterns if they know that there may be excess demand later. Ref. [107] used AI-based demand forecasting techniques for energy trading optimization. However, this model also does not consider supply uncertainties, which are widespread in DER-based microgrids. On the other hand [50], used a Monte Carlo simulation to predict future energy generation in a blockchain-based P2P trading platform; however, this work assumed that the DNO provides ancillary services. Additionally, while prosumers can store energy during off-peak hours to resell at higher rates during peak hours thanks to the inclusion of large-scale energy storage in the form of BEV or ESS in the smart grid, our work does not account for demand uncertainty or changing market dynamics [79]. Ref. [108] was the only model reviewed that modeled uncertainty using the unscented transform (UT) method to incorporate variables such as solar irradiation and wind speed in a decentralized energy network.

5.2. Research Gap 2: The Creation of Autonomous Pricing Systems and Trading Schemes for Energy-Enabling Individual Prosumers to Take a Passive Role in the Energy Markets

Currently, most works based on TE require the consumers and prosumers to decide the price, demand, and supply of energy. For example, in [60], the end user was required to decide the bid/ask price, while the market supplies it with information and applies time pressure. However, it is unlikely that consumers or prosumers will be able to actively take part in electricity markets or determine how much energy they need to consume or sell. Hence, autonomous trading strategies need to be built to achieve the goals of the user. For example, in [61,109] buyers can give preferences and an agent or algorithm matches them with sellers automatically. Ref. [67] developed an automatic bidding mechanism based on load and forecasting; however, this does not consider the preferences of the user, and hence, a blanket trading strategy is applied to all users.

In the future, there is a large potential in developing autonomous energy trading strategies where user intervention is minimal. Users should be able to set their preferences and influence the strategy [107]; for example, one user may want to minimize cost, whereas another may want to only use clean energy and using these preferences autonomous trading must take place to ensure a continuous energy supply for the end user.

5.3. Research Gap 3: Building Scalable Blockchains That Can Quickly and Safely Handle a Lot of Transactions

The majority of blockchain-based solutions have now been put to the test using case studies or computer simulations; nevertheless, in order to deploy blockchain technology in practice, it is necessary to comprehend and address system security and scalability issues. As previously mentioned, the Proof of Work (PoW) consensus mechanism is used in most blockchain energy research because it is the most popular [33]. However, PoW is not scalable, because it requires a lot of resources, and as the number and frequency of participants rise, the energy requirements of PoW-based blockchain networks may outweigh the advantages of decentralized trading.

In the future, some researchers have suggested that Proof of Stake (PoS) consensus mechanism to overcome this problem, as it is less resource-intense [110] and cannot be compromised using a 51% attack. However, PoS maybe compromised if a miner manages to gather 51% of the cryptocurrency in the network. Although this maybe unlikely further research needs to be done to understand and benchmark the safety of various blockchain technologies. Similarly, the current hardware, as well as the required hardware changes need to be analyzed for a successful implementation of blockchain-based energy systems.

Additionally, different transaction types, including DAG-based trading platforms, have been created to get around some of the drawbacks of blockchain, such as scalability and expensive transaction fees [111,112]. However, these systems are not yet fully developed and must be researched to understand their applicability and utility.

5.4. Research Gap 4: Implementing Blockchain-Based Solutions in Real Environments to Test the System and Identify Limitations

Blockchain technology is a novel technology, which has so far practically only been used for value exchange transactions on a large scale. Although there have been other real-world uses, they have not yet been carried out on the scale necessary for P2P Energy trading and related projects. As the network of blockchain nodes increases, issues such as forking and lag can occur, and these issues may only be identified through real-word applications of blockchain energy solutions in experimental environments before the technology is ready for mass implementation. Refs. [82,103,105] all suggested the importance of testing these solutions in real environments and [113] stressed the importance of increasing the number of real users in the system to test its robustness As mentioned above, currently, most research is only tested using case studies or secondary data, with "The Brooklyn Microgrid Project" being a notable exception [76]. Without testing on real microgrids, the key challenges or limitations of blockchain-based energy networks will not be revealed [114].

5.5. Research Gap 5: Making the Use of Blockchain-Based Energy Systems Practicable Requires the Development of Conflict Management and Dispute Resolution Tools

Almost no work has been done on the conflict management or dispute resolution of blockchain-based energy trading systems. To protect privacy, most works in this area protect the identities of the buyer and seller, with the assumption that smart contracts will be executed seamlessly. However, this seems to be an incorrect assumption. As suggested in [115], there are many limitations of smart contracts and their practical application will be limited until these limitations are overcome. Furthermore, as suggested in [49], regulations are quite underdeveloped in this area, making implementation of blockchain-based smart contracts even more difficult.

5.6. Research Gap 6: Creation of Workable Payment Methods That Are Widely Used and Approved to Ensure That Individual Users of the Blockchain-Based Energy Marketplaces Have Easy Access

The development of practical and implemental payment systems for energy trading is another key area for future research. The existing literature using smart contracts assumes that payments are made using cryptocurrency [116]. In smart contracts, the cryptocurrency is "locked" prior to a trade and transferred to the seller upon successful delivery of electricity. Currently, most individuals are used to post paid monthly electric bills. Additionally, most individuals may not want to keep high amounts of capital in cryptocurrencies, at least in the near future, and this may cause an impediment in smart contract implementation.

To overcome this problem, there have been suggestions of credit based smart contract settlements where a user will not have to hold large amounts of cryptocurrency [117]. This may, however, defeat the purpose of a decentralized energy trading system in the first place. If a creditor is paying a user's electric bills, it may have access to energy use patterns and other personal information, resulting in a breach of privacy. Future research on blockchain for energy must focus on making blockchain-based energy systems more accessible by overcoming these challenges.

6. Conclusions

Blockchain is a relatively new idea that has found use in a variety of industries, including the energy sector. Blockchain has attracted a lot of attention because of its decentralized nature and security, since it may be used to address issues that DERs confront. Although some of these applications have been implemented in the real world, such as the Brooklyn Microgrid Project, they have mostly been examined through case studies and simulations. Additionally, it may be predicted that there is still a long road ahead until blockchain technology is widely adopted in the energy industry, particularly smart grids, due to its difficulties and restrictions.

Based on a systematic review of 92 research publications, the following contributions have been made by this article:

- **Analysis of key blockchain technologies utilized in smart grid applications.** The main blockchain technologies applied to smart grid applications were examined. As a consequence, it was discovered that Ethereum is now the most popular blockchain for smart grid applications; nevertheless, it was noted that this is more of a convenience than a need. The advantages and disadvantages of different technologies and consensus mechanisms were also covered.

- **A review of smart grid issues.** The article discussed different smart grid issues that were resolved utilizing blockchain technology. The necessity to decentralize energy networks in order to lower costs and boost efficiency was shown to be the topic that was most frequently mentioned, and studies have indicated that blockchain technology is a suitable answer to this problem.
- **Classification of recent research (into four categories).** It was found that the present research on smart grids with blockchain technology may be broadly categorized into four categories: namely; P2P Trading, Electric Vehicles, Demand Response, and Privacy and Security.
- **Important research gaps (six).** Six significant research gaps were identified through the examination of the existing state of the art and must be closed before blockchain energy efforts can be broadly used effectively. The scalability of blockchain technology has been cited as a major issue in the majority of research studies, as there are significant time and resource limitations if large volumes of continuous transactions are made in the energy markets.
- **Potential future trends (six).** Based on the current trends and needs of smart grid energy markets, six potential future trends for **blockchain-enabled smart grids** have also been identified.

Blockchain technology is a rapidly growing field of study with several real-world applications. To leverage blockchain as an enabler for decentralized power distribution systems and smart grids, researchers from across the world have created a variety of solutions and performed studies. There are still significant gaps that will impede the development of blockchain technology, despite the fact that numerous ideas have been put out and proof of concepts have been shown. In order to enable researchers to build upon existing solutions and give non-technical people a comprehensive view of blockchain enable smart grid applications, this article reviews the existing solutions in order to provide a comprehensive analysis of the current state of the art, research gaps, and direction.

Funding: This research received no external funding.

Acknowledgments: This work was conducted as part of the Industrial Systems of the Future research program at the University of Cambridge, Cambridge, UK.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Network Visualizations of the Relevant Literature (Using VOS Viewer)

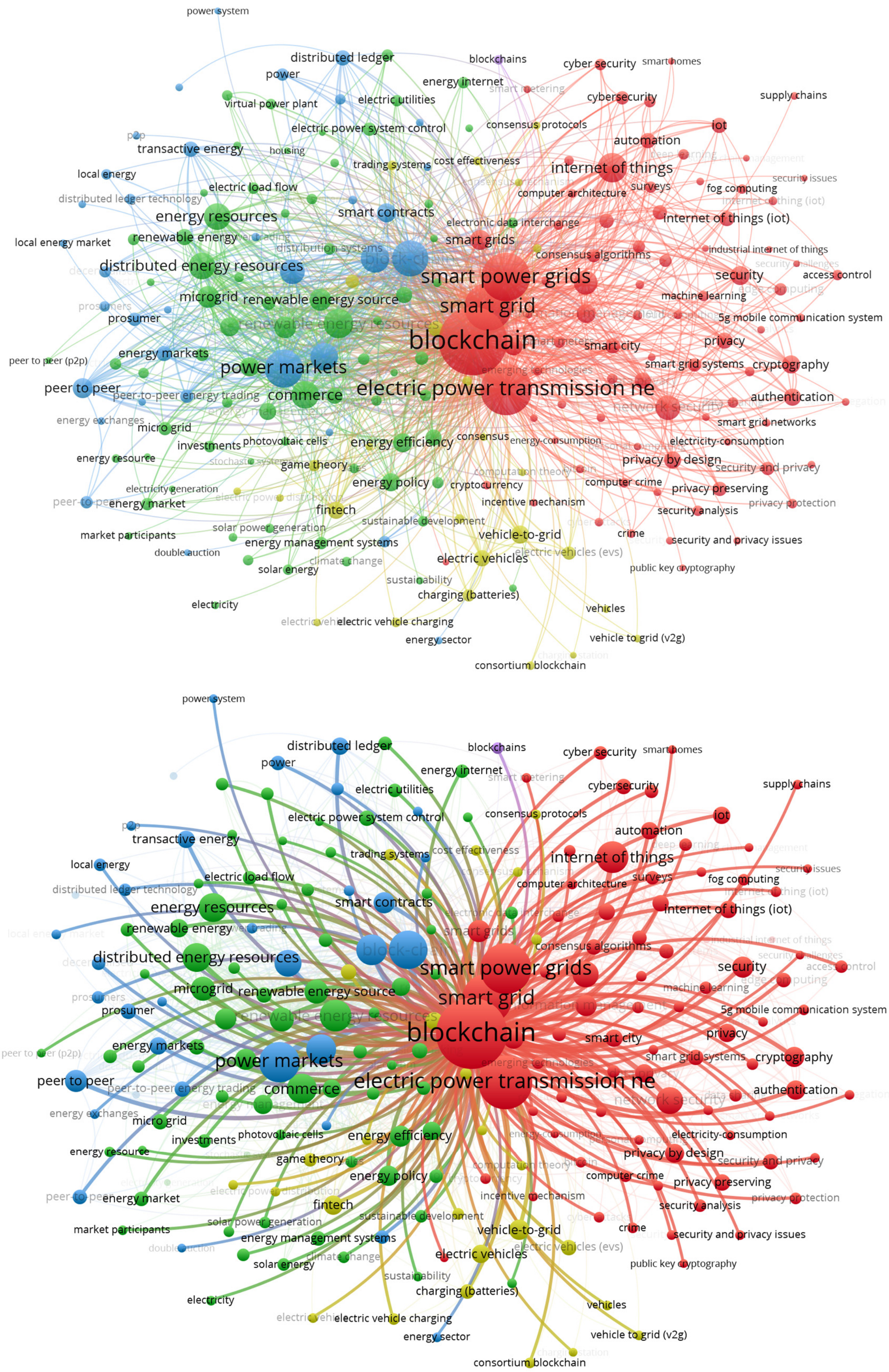

Figure A1. *Cont.*

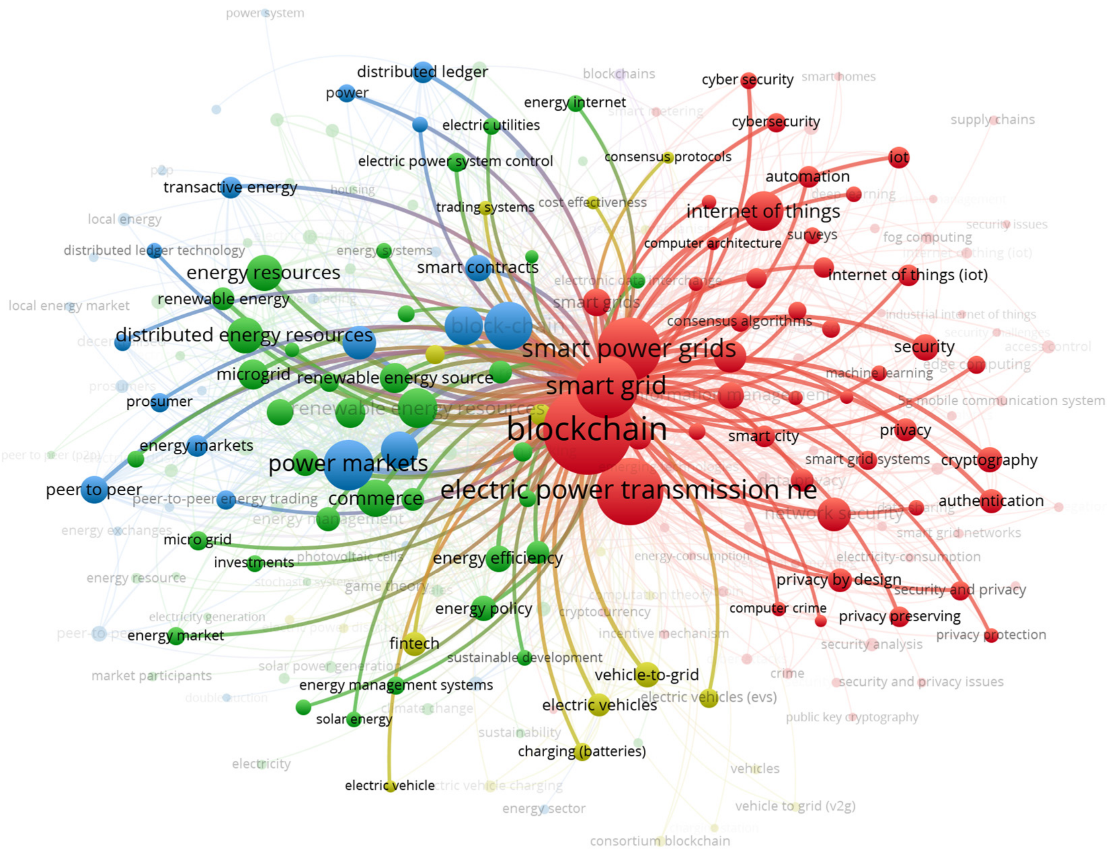

Figure A1. Keyword co-occurrence analyses (using VOS Viewer)—three views.

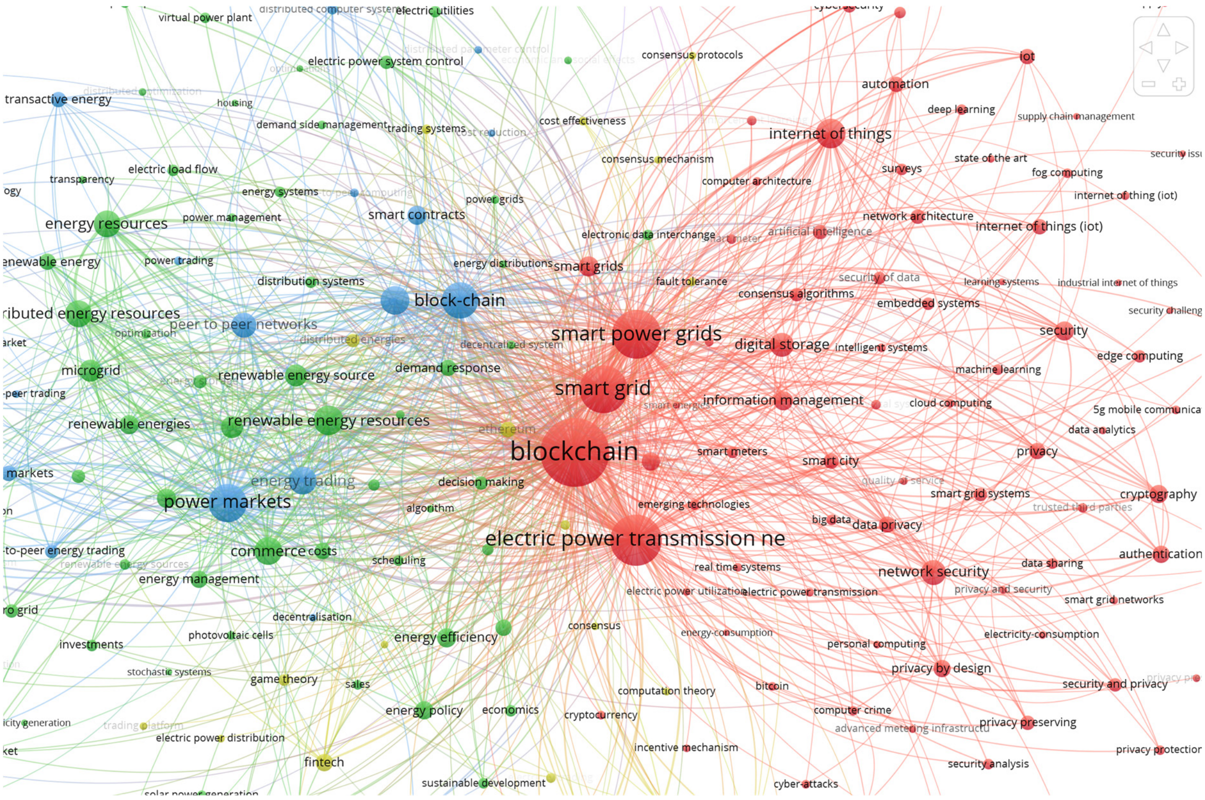

Figure A2. Keyword co-occurrence analysis (using VOS Viewer)—a zoomed-in view.

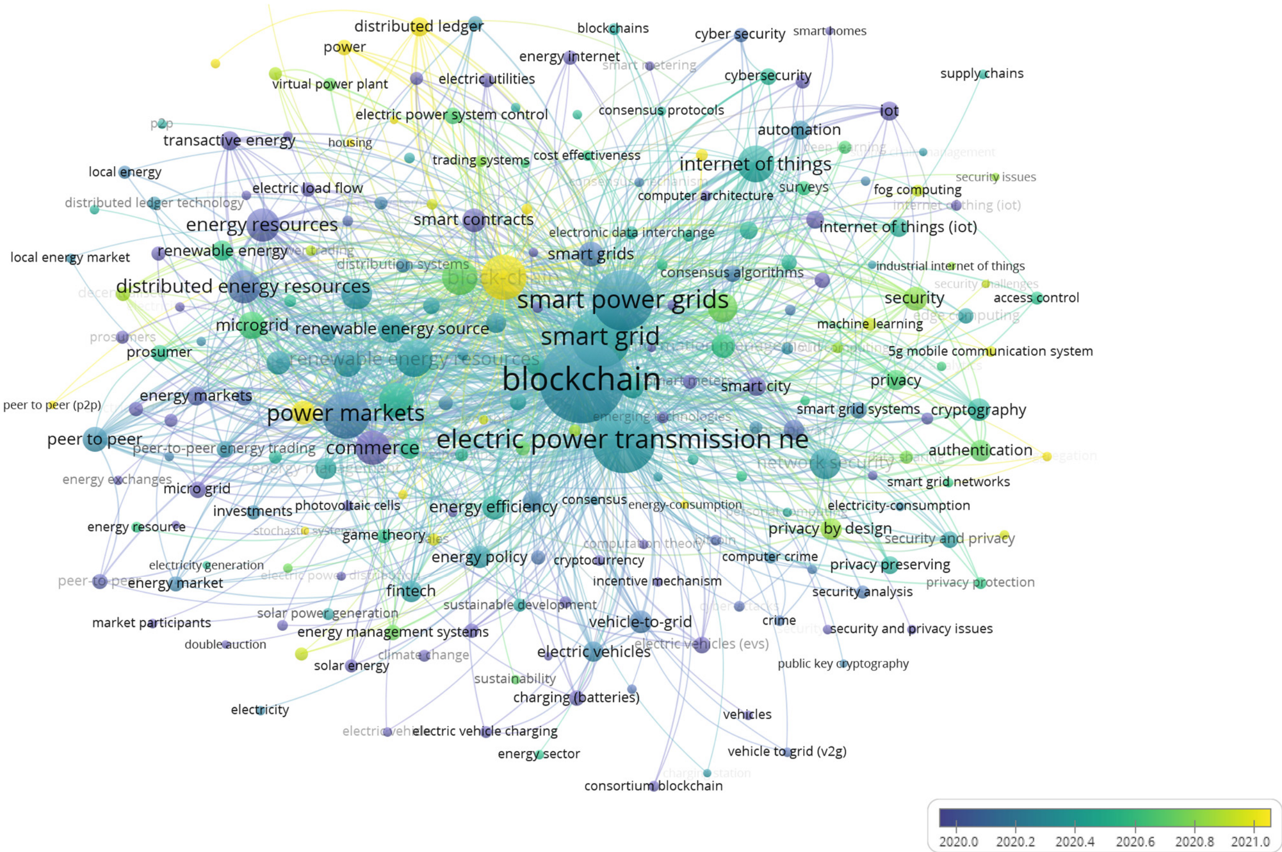

Figure A3. Keyword co-occurrence analysis (using VOS Viewer)—a time-based view.

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