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Review

Blockchain-Based Smart Renewable Energy: Review of Operational and Transactional Challenges

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Abstract: Blockchain has peculiar characteristics among various digital technologies due to its decentralised and cryptographic properties. The combination of intelligent energy systems and blockchain can innovate new forms of transactive energy and navigate the digital journey to transform the future of renewable energy systems. This review studies various blockchain implementations in the smart energy domain and presents the findings on operational and transactional challenges in a blockchain-based smart renewable energy system. We also identify the differences between operations and transactions in smart energy systems. Furthermore, we identify the most pronounced cryptocurrencies in different studies. The findings highlighted various challenges concerning the implementation of blockchain-based smart energy systems. We identified how these challenges spawn across operational and transactional deliverables. Building on these findings, we discuss various challenges impacting the operational and transactional domains, which we believe have significant value for researchers, practitioners, policy makers, entrepreneurs, and start-ups. It will provide long-term benefits to humankind in fulfilling energy requirements, promoting sustainable energy use by developing countermeasures to combat identified challenges and leveraging the optimal use of blockchain technology.

Keywords: blockchain; smart energy; transactive energy; transaction challenges; operation challenges; smart energy

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1. Introduction

Blockchain is an innovative technology comprising a decentralised ledger, indicating that information ownership is not under central governance. Fundamentally, there is no central control in the blockchain. Ledger indicates a platform where information about changes is stored. It can be defined as a distributed/decentralised database that contains an ordered list of various records connected through links called chains. A blockchain comprises an ordered sequence of nodes/blocks and links, with nodes/blocks storing information and chains connecting them. Blockchain technology refers to techniques and computer infrastructure for generating, storing, and reusing blocks. The basic concept behind blockchain is that a distributed database shared among participants contains a record of all transactions. A majority of the participants confirm that every transaction is protected using strong encryption and cryptographic controls to prevent the ledger from allowing fraudulent transactions to pass collective verification. A record can never be changed once it is made and approved by the blockchain [1].

Cryptocurrencies popularised blockchains that allow for the public availability of transaction records. Since then, plenty of new applications have surfaced based on this novel technology [2]. Such applications comprise a network wherein connected participants interact with others to exchange products and services. Third parties cannot read the information between interacting parties because it is cryptographically encrypted; hence, only authorised users can access it. Blockchain technology's advantages are the distributed ledger, decentralisation, information transparency, tamper-proof architecture, and openness [3]. Various sectors, such as banking, finance, hospitality and agro-business, have adopted this technology. The smart energy sector also widely accepts this novel technology transition. The transition of the renewable energy sector, particularly concerning decentralisation and digitalisation of the energy distribution and management domain, is gradually gaining pace. The energy industry is gradually entering the smart energy era using modern Internet-based technologies. Blockchain is one technology whose introduction has wholly reshaped the renewable energy ecosystem. With the popularity and successful use cases of blockchain implementation in various industries, this novel technology can significantly impact smart energy management. While blockchain technology in smart energy distribution is gaining popularity, smart energy service providers and consumers face many challenges. This article examines and studies works concerning blockchain implementation in smart grids to identify transactional and operational challenges. Blockchain-enabled smart grids face several transactional challenges, such as various aspects of transactive energy, including energy trading, the payment experience, payment type, and transaction cost. These transactional factors are directly related to customer experience and must be taken as vital components because transactional drivers are the primary building blocks of smart grids. Several studies such as [4] have highlighted the importance of the transactional aspect, discussing the value of the transactional component in peer-to-peer energy trading model development; [5] highlights the importance of the transactional aspect of energy trading based on blockchain, and [6] informs how to address various issues related to blockchain-based energy transaction systems. Consequently, various other studies on blockchain-based smart grids have highlighted the importance of the transactional system as a core component of smart grids. Similarly, smart grids' operational aspects cover day-to-day activities such as maintaining the internal system, resource addition, maintaining standards, performance tuning, complying with regulatory norms, managing demand-supply, and handling cybersecurity. The importance of the operational aspect of blockchain-enabled smart grid has been highlighted by various works, such as [7] through market analysis, [8] by comparing different operational parameters, [9] by highlighting asset management as a critical operational function, and [10] by proposing a vision to optimise physical operations. Other challenges might be studied using different perspectives; however, we identified a research gap concerning the challenges of blockchain-based smart grids and realised the need for a focused study to identify transactional and operational challenges. The literature contains works that highlight the importance of operational and transactional aspects. Transactional and operational challenges affect smart grids significantly; hence, identifying these challenges allows for developing countermeasures to safeguard smart grids from adverse effects and address these issues. Transactional and operational aspects comprise a significant portion of smart grid service delivery.

This paper focuses on analysing the impact of blockchain on transactional and operational dimensions. We broadly study the operational and transactional aspects of blockchain-based smart energy management. To the best of the authors' knowledge, the literature has no study addressing blockchain-based intelligent energy's operational and transactional challenges. A substantial body of knowledge exists concerning industrial efforts to use a holistic approach to study challenges; however, this literature review focuses on the transactional and operational challenges related to smart energy.

We analyse the following research questions in this review:

I. How are transactional and operational challenges distributed in the blockchain-enabled smart energy domain?
II. Among the transactional and operational components, which is more dominant in the literature?
III. Which cryptocurrency is gaining traction in conjunction with blockchain in the smart energy field?

This study has the following primary contributions to the literature within the context of the provided research questions:

I. Navigating the right direction concerning blockchain-based smart energy implementations in the real world to overcome potential operational and transactional challenges.
II. Strengthen blockchain-based smart energy start-ups, allowing them to anticipate and overcome critical obstacles and promote sustainable renewable energy.
III. Help understand cryptocurrency distribution.
IV. Use research findings to fulfil research gaps.

We answer these research questions by analysing various blockchain implementations in smart grids/energy distribution systems. We analyse blockchain implementations in the transactive energy domain and draw conclusive facts on transactional and operational challenges. This review will guide researchers and professionals to analyse the blockchain technology that best suits smart energy distribution, considering the transactional and operational aspects. The remainder of this review is structured as specified: Section 2 outlines the literature review concerning blockchain overview, smart energy, and related topics. Section 3 discusses the study methodology, indicating the approach and criteria used in this study. Section 4 summarises the study findings, highlighting the significant transactional and operational challenges elaborated further in Section 5. Finally, Section 6 presents the conclusion, summarising findings and providing future research directions.

2. Review

2.1. Blockchain

Blockchain is a decentralised digital distributed ledger technology. A distributed network of computing nodes called a peer-to-peer (P2P) network generates and collects a series of transactions that may represent the transfer or exchange of money or digital assets such as information, services, or goods [11].

A blockchain network comprises several computing nodes, each of which utilises a consumer to validate and send transactions between network users while storing the most recent network update [12]. A decentralised consensus mechanism among nodes creates a time-stamped data block (containing these transactions) according to pre-set protocols. The newly formed block also references the previous block (parent block) in the form of a cryptographic hash linking the blocks [11]. Blockchain is rapidly gaining traction as a critical technology to secure future commercial and economic competition around the globe. In the developing sharing economy, it facilitates trust and security [13]. All blockchain network participants can see and observe the blocks at any time; however, blocks cannot be changed, ensuring the ecosystem's transparency [14]. Although blockchain was initially believed useful for digital currency applications, experts quickly realised that it might be useful for various segments of society, industry, and business, including the energy sector [12]. Adaptability allows its use in various energy systems such as peer-to-peer energy trading and asset management. Blockchain technologies offer significant benefits such as minimising transaction costs, improving system resilience, and enhancing system security. Blockchain technology also improves system transparency, ensures accountability, protects privacy, and allows the creation of new business models and markets. Blockchain technology will inevitably acquire scalability at lower operating expenses as it matures. As a result, blockchain technology will become even more critical in creating ideal decentralised modes of operation and transactions to rapidly expand energy management verticals [15]. Blockchain has great potential for smart energy applications, specifically energy efficiency. It is a promising breakthrough that may be applied to various smart grid applications, including renewable energy, electric vehicles, bill payment, grid operation management, and transactive energy [16]. Smart energy management contracts based on blockchain can help bridge various gaps in selling and buying electrical energy by providing flexibility, additional security, and convenience, which substantially benefits business stakeholders and customers. In general, users would have access to rich and valuable information about daily energy consumption and expenses. Consumers can also plan and forecast their energy consumption [12]. One of the earliest use cases was presented in April 2016, where decentralised energy was transacted directly between neighbours in New York via a blockchain system, demonstrating that energy producers and consumers could execute energy transactions [17].

2.2. Blockchain Classification

Several criteria are used to classify blockchain into permissionless and permissioned systems. Permissionless networks are decentralised ledger platforms that allow anyone to publish blocks without permission. Permissionless blockchain systems are frequently used in open-source software that anyone can download and use for free. Because everyone can publish blocks, anyone can read the blockchain and perform transactions [18]. Any peer can join or exit the network as a reader or writer at any point. Surprisingly, there is no centralised institution in charge of membership management or the ability to restrict unauthorised readers or writers. This openness indicates that any peer can read the published information [19]. Bitcoin was the first permissionless blockchain [20]. A permissioned blockchain comprises a system with an authorisation layer that sets the scope of users and grants system access to the intended group [21]. Permissioned blockchain networks function on private, segmented networks with identified, more trustworthy members owing to identifiability. As a result, less costly consensus techniques may be utilised, resulting in improved performance, lower transaction throughput, reduced transaction confirmation delay, and lower costs. Furthermore, the network can be segmented such that nodes only have access to and verify transactions for which they have been granted authorisation. It is excellent for protecting the privacy and data sensitivity of the network [22].

2.3. Smart Energy

As a new paradigm of the old grid, the smart grid was proposed to integrate green and renewable energy technology efficiently. Smart grid technology allows transforming the electrical system from a traditional power grid to an intelligent power network, resulting in significant gains in energy efficiency and sustainable energy integration [23]. The term "smart grid" refers to the modernisation of all aspects of energy systems, from generation to consumption [24]. The internet-connected smart grid, also known as the Internet of Energy/Smart Energy, is an innovative approach to ensure the exchange of energy data anytime and anywhere, leading to the creation of a sustainable society. The traditional centralised grid system, on the other hand, has faced significant challenges in integrating and coordinating extensive and growing connections. As a result, the smart grid architecture is shifting from a centralised to a decentralised model. Various sectors have recognised the potential of blockchain technology. It is realistic to believe that the energy business, particularly smart energy, can benefit from blockchain-based systems to self-regulate and manage transactions and contractual data [25]. Furthermore, blockchain technology has been widely deployed in different Smart Grid scenarios because of its excellent characteristics [26]. With the recent rise of blockchain in the new ICT platform development, it is expected that many other sectors concerning smart grids will advance with blockchain integration [27]. With the growing use of renewable energy sources in the energy mix, new market approaches to pricing and distribution are required for volatile and decentralised generation [28].

2.4. Integration of Blockchain in Transactive Energy

The term Transactive Energy (TE) was first described by the Grid-Wise architecture council as "A collection of economic and control mechanisms that allows the dynamic balance of supply and demand throughout the whole electrical infrastructure utilising value as a key operational criterion". The market price is frequently used to symbolise "value" in this definition [29]. Transactive energy is a practical approach for peers to exchange and trade energy. In the field of energy systems, Aitzhan and Svetinovic [30] proposed a blockchain-based approach to devise a token-based, decentralised energy trading system. The study showed that the energy trading system gives agents an anonymous communication channel and the ability to trade energy ownership in the smart grid via distributed smart contracts. Blockchain technology is being examined in the energy trade because of its decentralisation, anonymity, and trustworthiness advantages. The blockchain is an open distributed ledger that keeps track of transactions in a permanent and verifiable manner [31]. An energy market, service providers, generation corporations, transmission and distribution networks, prosumers, and other integrated components comprise a transactive energy framework [32]. TE systems are designed to dynamically balance electrical demand and supply within the electrical grid using sophisticated information and communication technologies, taking advantage of advanced control and transactional and operational features [33]. TE is a relatively new notion that has received a lot of attention. It combines information and energy to allow transactions, offering coordinated self-optimisation [34]. Peer-to-peer energy transactions based on DLT and transactive controllers in Local Energy Markets (LEMs) are the most likely evolutionary scenarios for future smart grids, considering that old centralised energy systems are no longer sustainable [17]. The decentralised nature of blockchain creates a transparent and trustworthy environment for network participants to connect directly and conduct secure peer-to-peer transactions. The operation of the transactive energy system may be too complicated to meet market participants' objectives. Energy flows and financial transactions throughout the distribution system must be reliable and transparent to all parties, as the transactive energy system allows joint responsibility for managing energy and the market [10]. The transactive control technique is the most crucial aspect of the TE system design. A sophisticated and robust control solution for transactions between different levels and same-level feeders is the utmost priority. Sophisticated automated solutions can also help with system security and reliability. The underlying premise of the TE framework, notably the flexibility of each customer to join the traditional power market with the distributed household generation, becomes highly conceivable once the solution is proven functional and widely applicable [35]. The energy sector must deal with increasing complexity as electric power networks worldwide rely more on intermittent renewable energy, distributed energy resources, and advanced digital technologies. Blockchain technology can enable a distributed software architecture for energy markets [36]. The use of blockchain technology has the potential to address this complexity. The surge in cryptocurrency value and popularity has shown that blockchain may be used to underpin an extensive, distributed network that records transactions in a timely, immutable, and transparent manner [37]. Blockchain-based technologies can play a critical role in energy sector transformation by providing decentralised interfaces and systems and an alternative to the current energy market structure [14].

Despite the rising complexity of the increasingly decentralised energy system, blockchain has the potential to optimise energy management operations in practically all stages of the value chain [38]. Active local integration of renewable energy sources into the energy system is one of the many benefits of blockchain in energy markets. Integrating blockchain as a peer-to-peer (P2P) electricity trading system [39] for plug-in hybrid electric vehicles shows blockchain's wide acceptance as a disruptive technology in the energy sector. Similarly, ref. [40] highlighted that the active local integration of renewable energy sources into the energy system is one of the many benefits of blockchain in energy markets. Along with the unified energy blockchain for secure energy trading [31], various scenarios have highlighted the possibilities of blockchain in the energy sector.

Table 1 shows an overview of the selected articles on blockchain technology and its implications for transactive energy. Various blockchain models have been developed to address versatile transactional needs. Table data indicate the wide use of blockchain technology for smart energy systems in the EV context. It is a positive indicator suggesting a bright future for renewable energy sources; blockchain fosters the adoption of environment-friendly EVs, reducing the carbon footprint.

Table 1. Blockchain implications for transactive energy.

Blockchain Technology	Implications	Strength	Refs.
Byzantine-based blockchain consensus system	Energy trading process between Electric Vehicle (EV) and distribution network (DN)	Reduced latency, improved throughput	[41]
Decentralized Transactive Energy	Digitalization and interoperability of transactive energy	Establish sustainable transactive energy community	[42]
Consortium blockchain.	Secured smart grid model	Better defense against cyberattacks	[43]
Security blockchain	Power trading mechanism for smart grid employing wireless network.	Improve the long-term viability and scalability of renewable energy producers	[44]
Integrated blockchain-based energy management	Respects physical microgrid constraints and implements a bilateral trading mechanism	Highest total social welfare	[45]
Smart contracts	Integrated energy trading	Simplifies the trading process into two stages	[46]
Smart contract	DER energy exchange via AMI	Improve cyber resilience of smart grids and secure transactive energy applications	[47]
Proportional fairness	Voltage regulation	Incentivize distributed energy resources to fairly participate in voltage regulation	[48]
Smart contract	EV charging in smart community	Higher utilities among the operator and EVs	[49]
Continuous Double Auction (CDA), Proof of State (PoS)	Transaction of electricity	Direct settlement of blockchain based transaction	[50]
Elliptic curve cryptography (ECC), PBFT consensus	V2G energy trading	EVs will be rewarded via a blockchain-based hierarchical authentication method.	[51]
Smart contract	EV charging and trading	Dependable, automatic, and protect privacy charging stations	[52]
Smart contract	Energy demand management	Enhanced, accurate demand-supply management	[53]
Elliptic curve cryptography (ECC), Smart contract	EV and charging pile management	Enhanced vehicle security	[54]
Smart contract	Smart grid monitoring	Efficient and tamper-proof platform	[55]

2.5. Integration of Blockchain in the Energy Market

The energy market refers to the primary product exchange market wherein buyers and sellers trade energy. Although centralised energy market structures have a small number of decision-makers, decentralised structures may have many participants, all of whom must coordinate different market aspects and business models, requiring specialised approaches [56]. The energy market is increasingly changing toward a distributed market where renewable energy can be traded, as indicated by the growing number of blockchain-based solutions for the distributed energy sector. The fundamental qualities of blockchain, such as anonymity, decentralisation, and transparency, have generated interest in the technology [57]. Blockchain-based technologies can play a critical role in energy transformation by providing decentralised interfaces and systems and an alternative to the current energy market structure [38]. In the energy sector, this novel technology offers hope that a safe and trusted digital transaction platform will allow consumers to actively engage with the energy market [58]. Blockchain technology, as a decentralised and distributed accounting system, is well suited for the energy market from a distributed generation perspective [46]. Various blockchain application models have been developed for energy trading and market design; [59] introduced a new digital currency called NRGCoin for a market having an externally fixed pricing function. The proposed model used locally generated renewable energy to buy NRGcoins regardless of market worth. Decentralisation in the energy market provides an essential platform for energy traders: [28] presented a comprehensive concept, market design, and simulation of a 100-household Local Energy Market (LEM) providing a decentralised market platform to trade local energy. Another study [60] highlights a distributed marketplace based on a consensus blockchain with autonomous features. Their approach considers the marketplace for trading electricity between households, and individual smart devices could be developed in several ways [61]. This study highlights the use of blockchain in peer-to-peer energy trading and indicates that blockchain can improve the transacting party's trust. A security and privacy-focused study [30] describes auction offering-based markets and crafted a private decentralised energy trading system based on tokens that allow peers to negotiate prices discreetly and securely. Another study [40] presents the notion of a blockchain-based microgrid energy market that eliminates intermediaries using a double auction market mechanism [62]. This study introduces a smart contract that executes a transactive energy auction without requiring monitoring by a trusted entity. It implements a Vickrey second price auction, ensuring that bidders make honest bids. Another study [39] introduced an iterative double auction energy market for p2p renewable energy trading. Another study on transactive energy systems using distributed ledger technology [63] put forward a p2p energy trading market scenario. Ref. [50] proposed a continuous double auction market where a buyer and seller first match the transaction. The same study also mentioned the feasibility of market mechanisms using a specific instance and the settlement procedure. Similarly, the transaction management platform also plays a crucial role in integrating blockchain in energy markets; demand–supply management is a critical operational challenge that can be addressed using an improved transaction management platform. Privacy is essential; ref. [30] highlights that the security and privacy of data used for consumption and trade pose significant problems. One of the typical transaction management platforms widely discussed in this literature review is the Privacy Preserving Energy Transactions (PETra), widely introduced in [54–56] for energy transactions in the transactive energy market. After referencing several research works using the literature concerning blockchain market integration, we conclude that the market is an integral aspect of transactive energy, supported by a transaction management platform. Table 2 lists different blockchain markets.

Table 2. The literature depicting the distribution of blockchain-based energy markets.

Literature	Market Model	Advantage	Refs.
Towards Resilient Networked Microgrids: Blockchain-Enabled Peer-to-Peer Electricity Trading Mechanism	Local energy trading market	Real-time energy trading with less intervention	[6]
A Blockchain-Based Load Balancing in Decentralized Hybrid P2P Energy Trading Market in Smart Grid	Hybrid p2p energy trading market	Reduction of cost and peak to average ratio of electricity	[64]
A Sustainable Home Energy Prosumer-Chain Methodology with Energy Tags over the Blockchain	Hybrid p2p trading market	Long term economic benefit	[65]

Table 2. *Cont.*

Literature	Market Model	Advantage	Refs.
Blockchain based uniform price double auctions for energy markets	Uniform-price double auction energy market	Enhanced efficiency, security, minimized blockchain overhead cost by installing computation modules	[66]
Blockchain for peer-to-peer energy exchanges: design and recommendations	Decentralized energy market	Support energy transaction in energy community by offering efficient and resilient way	[67]
Building a Community of Users for Open Market Energy	Local energy market	Enhance trust, guarantees security, integrity and resilience, preserve privacy requirements	[68]
Co-simulation Framework for Blockchain Based Market Designs and Grid Simulations	Distribution level energy market	Economic incentives aligned to physical constraints, more effective distributed energy markets	[69]
Crypto-Trading: blockchain-oriented energy market	Decentralized energy market	Optimize the energy trading with robo-advisor, creation of decentralized energy market	[70]
Decentralized P2P Energy Trading under Network Constraints in a Low-Voltage Network	P2P energy trading local markets	Economic benefits to user, energy is exchanged among users without impacting network constraints.	[71]
Decentralizing Energy Systems Through Local Energy Markets: The LAMP-Project	Local energy market	Downsize the overall electricity prices	[72]
Distributed Ledger Technologies for Peer-to-Peer Local Markets in Distribution Networks	Local energy market	Reasonable operating cost, competitive technological management capabilities	[73]
Fostering Consumers' Energy Market through Smart Contracts	Local energy market	Automatic energy exchanges	[74]
Hierarchical approach for coordinating energy and flexibility trading in local energy markets	Local energy market	Flexibility in trading and transaction flexibility	[75]
Peer-to-Peer Energy Markets: Understanding the Values of Collective and Community Trading	P2p energy market	Provide insights in developing P2P energy markets	[76]
Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges	P2p energy market	With P2p prosumers can minimize cost of electricity	[77]
State-of-the-Art Analysis and Perspectives for Peer-to-Peer Energy Trading	P2p energy trading market	Key aspect of P2P energy trading are identified	[78]
Synchronization Games in P2P Energy Trading	P2p energy market	Identification of profitable strategy in P2P trading	[79]
Viability analysis of a decentralized energy market based on blockchain	Double auction energy market	Offers and bids are exchanged on a double auction model	[8]
A novel electricity transaction mode of microgrids based on blockchain and continuous double auction	Continuous double auction market	Adaptive aggressive strategy to control frequent price fluctuation	[50]
Peer-to-peer and community-based markets: A comprehensive review	P2p electricity market	P2P designs carters best use for maintaining privacy	[80]

Table 2 provides an insight into the relevant articles on blockchain-based energy market distribution, describing the market type. Most articles have indicated blockchain-based peer-to-peer energy trading markets. Several articles also justify that the type of local energy market determines the appropriate blockchain approach. Some studies highlighted auction-based energy markets and decentralised energy markets for trading. These findings are used to classify the market into four segments, indicated in Table 3 and Figure 1.

Table 3. Market type distribution.

Market Type	Count
P2P energy trading	8
Local energy market	7
Double auction energy market	3
Decentralized energy market	2

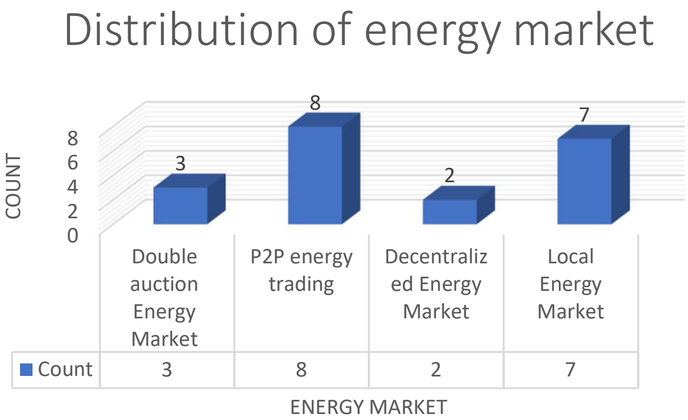

Figure 1. Graphical representation of energy market distribution.

Overall, the literature review concerning market type provided a more refined view of the market distribution; regardless, most research is mainly conceptual or based on incomprehensive studies and limited practical simulation. The papers assessed for blockchain application also reveal the bounded research on blockchain-based energy markets. However, designing and implementing a real-world marketplace is more complex.

3. Methodology

This study focuses on blockchain implementation in the smart energy domain. The primary objective of this review is to provide findings after analysing the operational and transactional challenges that have an active impact on blockchain-based smart renewable energy systems. Additionally, this paper identifies the weightage of operational and transactional challenges. Finally, we briefly analyse cryptocurrency's dominance in blockchain-based smart energy. Based on these objectives, we evaluated articles that examine blockchain applications in smart energy. We scanned, evaluated, and curated information based on this research to assimilate a relevant operational and transactional challenge dataset.

3.1. Search Criteria

For this review, we used the following inclusion and exclusion criteria to identify and select various articles on blockchain implementation in the smart energy domain:

3.2. Inclusion Criteria

The following inclusion criteria are used for this study.

- Published in English.
- Peer reviewed.

- Paper discusses blockchain implementation in the energy sector.

3.3. Exclusion Criteria

The following exclusion criteria are used to select relevant articles.

- Papers that discuss only concepts.
- Papers that do not mention blockchain as a core technology

3.4. Study Selection

We started the literature evaluation by searching for the keywords "Blockchain in smart energy", "Renewable energy and Blockchain", and "Blockchain and transactive energy" on Google Scholar. The preliminary relevance of the text was judged by its title. If the article appeared to examine the technique of the literature review process based on the title, we retrieved the complete reference, including the author, year, title, and abstract, for further analysis. Overall, the inclusion and exclusion criteria were used to create a comprehensive database of 55 entries for various analyses. The results were then recorded in an Excel spreadsheet for subsequent analysis, including the citation count (as of 15 October 2021 in Google Scholar) and other relevant information.

3.5. Data Extraction and Analysis

After studying the selected articles on blockchain and smart energy, we first split the literature for data collection to perform the following analysis. The initial 15 literature volumes were selected to study blockchain technology and its implications in transactive energy. We analysed the blockchain technology and implementation domains. The following form summarises the data extracted format from the literature.

Blockchain Technology	Implications	Strength	Refs

The subsequent 20 literature volumes were used to further study the energy market, including the distribution of the energy market from the blockchain technology perspective. The following format was used to record the type of market from this analysis.

Literature	Market Model	Advantage	Refs

The final 20 literature volumes were used to identify the leading operational and transactional challenges, which is one of the main objectives of this study. The following form records the data extracted from this analysis.

Articles	Authors	Published Year	Citations

Further analysis of the last 20 literature volumes provided operational and transactional challenges that were individually analysed to provide the final observations concerning operational and transactional challenges.

4. Findings

The literature specifies various operational and transactional challenges. These challenges are distinctly significant depending on the nature of developments and deployments. Altogether, 55 articles were analysed to review several subject matters. We found that distributed ledger-based technologies such as blockchain might help automate and digitise smart renewable energy transactions. Blockchain implementation can drive significant advancements in energy management and distribution. The renewable energy management system is a complex domain. Calculative projections and counter-strategy need to be developed in advance. Smart renewable-energy systems majorly comprise operational and transactive aspects. The success of smart renewable energy projects entirely depends on operational and transactive characteristics. The effective utilisation and management of these two domains in smart renewable energy can lead to a prosperous energy community. The findings suggest that blockchain applications in key managerial domains, such as smart energy operation and transactive energy management, are evolving. However, various operational and transactional challenges must be handled correctly for renewable energy operation and trading sustainability. On the one hand, these findings address research questions; however, they raise questions about new energy solution design to balance operational and transactional challenges while maintaining low investment needs and flexibility concerning the demand-based interaction levels at the prosumer level.

4.1. Operational Challenges

The literature broadly lists operational challenges concerning scalability, regulatory framework and standards, cybersecurity, operational cost, performance, interoperability, privacy, skill requirement, storage management, and limited segment benefit.

4.1.1. Scalability

Scalability is an important aspect of the operational expansion aspect of blockchain-based smart energy. Although distributed ledger technology has many other benefits, scalability is a significant roadblock when using blockchain in real-world scenarios. Scalability encompasses three aspects: throughput, storage, and networking. Performance is measured using the number of transactions per block and the time between blocks; storage is determined by the data created, and networking is evaluated using data transfer [81]. As the number of participants in the block grows, the retrospective aspects affect throughput, storage, and networking. Blockchains require all nodes to validate all transactions, requiring a complete copy of the blockchain history, causing scalability challenges even in the smallest market [82]. Ultimately, this shall strongly impact the operation of intelligent energy management and distribution [18,49,76–84].

4.1.2. Regulatory Framework and Standards

Blockchain implementation in the renewable smart energy domain has faced several challenges due to a lack of regulatory framework and standards. Various researchers have indicated that this lack has created many problems in smart energy distribution and management. Numerous research works suggest that blockchain technology's potential extends beyond peer-to-peer energy trading, and the fundamental problems are related to the role of regulatory frameworks [85] and technology's maturity. The absence of generally recognised standards prevents integrating many connected devices in smart energy systems, creating a critical barrier for the overall blockchain-based smart energy system [26]. Refs. [76–78,86–89] discuss the frameworks and standards as significant challenges in smart renewable energy operation.

4.1.3. Cybersecurity

Cybersecurity has evolved as one of the critical challenges in the operation of a smart energy system. Energy systems' dependency on network infrastructure and the internet has led to the emergence of cybersecurity as a significant challenge for smart energy system operation and distribution. Although the modern electrical grid has many advantages, such as ubiquitous control and self-healing, it poses significant cybersecurity concerns. The combination of unsecured communication protocols, IoT security vulnerabilities, and the rapid advancement of cyberattacks and malware, in particular, might have severe results, including widespread blackouts and brownouts [90]. Exploring blockchain cyber risks, vulnerabilities, and mitigations in the context of safeguarding the grid's edge and offering more secure transactive energy solutions would be a massive benefit to grid cybersecurity and resilience research [47]. Interconnectedness is a critical aspect of smart energy systems, and cybersecurity is a fundamental challenge.

4.1.4. Operational Cost

The use of blockchain in smart energy systems may offer several benefits; however, operational cost management is one of the burning challenges. Various researchers have indicated that with the growth of blockchain-based smart energy systems, operating cost is likely to increase significantly. The running expenses of the public blockchain system, including the necessary processing power and energy consumption, are quite expensive [42]. Moreover, climatic conditions increase the energy procurement cost during peak loads and reduce it during off-peak periods [91]. Balancing costs considering such changing dynamics is another major challenge. Refs. [80,85,86,89] describe cost as a significant challenge.

4.1.5. Performance

Blockchain-based smart energy systems deal with a tremendous amount of data. Smart energy grids acquire individual customer usage data, evaluate them, and optimise operations to fit diverse demand patterns by processing data using computer technology. Power companies are upgrading their infrastructure to use intelligent digital technology such as automated meter reading to modernise their grids. A large quantity of data are collected and evaluated, with the results being saved for future reference and reuse [92]. Data management is a complex task, and smart energy system performance creates challenges in the longer run. If concurrency management is implemented by locking the whole database, or even only one data input is accepted from users, the database would become less resilient and perhaps sluggish. As a result, the smart device account balance updates must be conducted with reduced frequency, resulting in lower allocation efficacy [60]. Refs. [49,82] discuss performance as a critical challenge in smart energy systems.

4.1.6. Interoperability

In addition to other vital challenges identified in this study, interoperability is another major challenge in blockchain-based smart energy systems. Refs. [38,87] highlight interoperability as a significant challenge. Similarly, ref. [93] raises concerns about conversion, stating there is a loss when energy from different sources is converted or transported. Interoperability of blockchain-based systems comes as a critical challenge for three significant reasons: survivability, offering various service types, and the blockchain system itself [94]. Network congestion, overloading, and voltage variation may occur due to integration and interoperability difficulties.

4.1.7. Privacy

Privacy is another primary concern for blockchain-based smart energy systems. Many researchers believe privacy preservation is a major challenge when using blockchain in a connected system [84]. Blockchain benefits such as integrity and non-repudiation allow the system to be accepted as a part of the base infrastructure. However, privacy disclosure is a major issue for most blockchain-based trading methods [95]. When using blockchain technology in the energy sector, extra attention must be paid to the inherent conflict concerning privacy issues, especially since residential energy usage is personal data. Refs. [81–83,93] discuss privacy as a significant challenge.

4.1.8. Skill Requirement

Skill requirement is another critical challenge for blockchain-based smart energy systems. The operation of a smart energy system requires highly skilled technical resources. Wu and Tran [96] discuss skill shortages as bottlenecks in applying blockchain technology in sustainable energy systems. Refs. [49,87] highlighted skill requirements as an essential factor.

4.1.9. Storage Management

As blockchain deals with a tremendous amount of data, blockchain-based smart renewable energy systems have always considered storage a challenge. Storage infrastructure would be critically tested when the chain grows to tens of thousands or millions of transactions. New network nodes might have sluggish CPU performance [97], increasing operating costs for managing storage [98]. Highlights the challenge of multilevel storage management related to blockchain's distributed nature [99]. Highlights the benefits of blockchain and smart contracts in the energy sector and identifies storage as a significant bottleneck.

4.1.10. Limited Segment Benefit

While the challenges discussed focus mainly on cost and technical effects, few researchers highlighted socio-economic aspects. Among other challenges, the premise that limited people benefit from the system is a significant concern. Ref. [100] discusses the influence of the big players on energy distribution and the polarisation of the shared benefits from energy trading. Similarly, ref. [53] describes how homes and small enterprises are considered small energy producers despite their significant contribution to energy trading. In addition, ref. [96] emphasised the segmentation and highlighted the risk arising from a single interest group.

4.2. Transactional Challenges

While various studies focused on smart energy systems' operation and technical aspects, we studied the transactional aspects and challenges. The study reveals several transactional challenges such as throughput, cost overhead, and time lag during payment and conversion.

4.2.1. Transaction Throughput

Most blockchain designs are based on Proof of Work (PoW). The two most important metrics for assessing the performance of a PoW blockchain are block frequency and block size. Because larger blocks induce propagation delay, increasing block size to maximise throughput increases latency [41]. The throughput of some blockchains is not equal to that of a shared data storage due to mining-induced delay [36]. A significant increase in the number of blocks stresses the chain, leading to throughput challenges for committing transactions. Refs. [78,79,86] highlight throughput and transaction per second (TPS) reduction as a significant challenge [89]. The possibility of only 15 TPS affects transactions as new functionalities and entities are added. In some cases, ref. [101] transaction throughput may not be sufficient to allow high-frequency power trading, and scalability issues may arise.

4.2.2. Cost Overhead

Smart-energy consumers are expected to bear the overhead costs of storage, technology, and electricity. According to T. Sawa [102], it is critical to determine cost savings when implementing blockchains for existing or new energy systems. In most cases [61], the energy utility business acts as an intermediary and makes a lot of money. This approach is expensive and inefficient since consumers must pay higher energy bills when purchasing electricity from a utility company and accept lower electricity profits when selling surplus power [58]. Highlighted cost overheads, and [103] mentions that the blockchain running cost is higher. Hence, implementing blockchain for energy transactions comprises cost overhead as a significant challenge.

4.2.3. Time Lag during Payment

As the number of entities and transactions increases, blockchain network overhead for the transactive energy system will cause payment time lags [47]. Latency affects real-time transactions, affecting the energy ecosystem. Another study [104] highlights a diminished transaction load on the blockchain-based transactive energy system, indicating payment time lag as a significant transactional challenge.

4.2.4. Convertibility

Most blockchain-based transactive energy systems are based on cryptocurrency. Introducing cryptocurrencies is a significant challenge affecting convertibility in the smart energy ecosystem. Cryptocurrencies, like Bitcoin, are highly volatile, increasing conversion difficulties. Selecting the base currency is another challenge since it is tricky to handle conversion rate fluctuations [89]. Hence, convertibility becomes a key challenge while implementing blockchain in transactive energy systems. In this section, we analysed various pieces of the literature regarding implementing blockchain technology in the smart renewable energy system and its operational and transactional challenges. The review identified various operational challenges such as scalability, regulatory framework and standards, cybersecurity, operational cost, performance, interoperability, privacy, skill requirement, storage management, and limited segment benefit. This review also identified several transactional challenges in blockchain-based transactive energy systems: transaction throughput, cost overhead, time delay during payment, and convertibility.

The Table 4 below highlights the summary of key findings along with associated risks.

Table 4. Summary of the key findings.

Challenges	Category	Related Articles	Risk
Scalability	Operational	11	Impact on smart grid service availability, consumer is impacted
Regulatory framework and standard	Operational	9	Regulatory fines
Cybersecurity	Operational	6	Financial, non-financial damage, reputation risk
Operational cost	Operational	6	Rise in expense, risk of hidden costs
Performance	Operational	4	Service degradation
Limited segment benefit	Operational	4	Risk of improper segmentation
Privacy	Operational	3	Identity theft, risk of targeted attacks
Interoperability	Operational	3	Risk of overloading, voltage variation
Skill requirement	Operational	2	Operation risk, service impacts
Storage management and requirement	Operational	2	Risk of service outage, no smooth service
Transaction Throughput	Transactional	7	Slow transactions, increased wait times
Cost overhead	Transactional	3	Risk of revenue reduction
Time lag during payment	Transactional	2	Reputation loss, poor customer feedback, delay in balance update
Convertibility	Transactional	2	Currency exchange risk

The findings from our study also establish that operational challenges are more dominant than transactional challenges in blockchain-based smart energy systems. Forty operational challenges were identified, compared to twenty transactional challenges. Operational challenges are more prominent than transactional challenges. Additionally, Bitcoin has the highest dominance among cryptocurrencies, highlighting its popularity. Our findings determined a single research work [28] highlighting a stable currency. The feasibility of future cryptocurrencies offering the stability of traditional currency must be considered.

5. Discussion

Reviewing various works regarding blockchain implementation in smart energy demonstrates that the technology has the potential for vast implementation domains in the smart energy sector. Blockchain advantages such as strong cryptography, privacy, and decentralised control offer a stronger connection between the smart grid and service delivery. Blockchain's popularity in other sectors significantly impacts the energy sector. The ecosystem appears to scale this technology to support smart grids' operational and transactional capabilities. However, various challenges raise concerns about long-term growth and reliable value addition in smart grids. The identified challenges must be adequately addressed before mainstream deployment and operation. Scalability is a significant challenge that blockchain technology must address. Initial technology deployment and operations might not be complex; however, regular operation increases data volume, requiring higher processing capacity, network and node complexity, and higher hardware sizing, which are significant hurdles. Smart grid operation and service delivery must be smooth. Addressing scalability challenges with an operational smart grid might be incredibly difficult. Additionally, capacity expansion, enhancing processing hardware for better encryption and decryption in an extensive network, and increasing storage capacity is a cost-intensive process; even small changes might cause huge cost overheads. These can lead to outages, blackouts and, in extreme cases, unequal energy distribution, becoming a serious concern. Distributed consensus mechanisms are currently being researched to eliminate this challenge, but a system that combines all desirable properties without substantial trade-offs is still a long way off. Another notable operational challenge related to blockchain technology is the lack of proper regulatory guidelines for managing this technology. The lack of guidelines and best practices creates difficulties in maintaining uniformity and adherence to best practices. The lack of a proper framework, practices, and standards creates ambiguity in operational excellence and service level integrations. The absence of regulatory guidelines can lead to situations where smart grid operations can be affected. This case is evident in most blockchain platforms, as they operate on cryptocurrency payments, and there is no regulatory control for standardising cryptocurrency in the blockchain environment. This tendency can seriously impact customers due to frequent rate fluctuations. Cybersecurity is another major concern regarding blockchain deployment. Although the technology is secured with strong encryption and cryptography, there are many situations wherein blockchain networks have been victims of major cyberattacks. Addressing cybersecurity concerns and maintaining proper offensive and defensive security is a significant challenge. It is a critical step that requires expert cybersecurity knowledge, experience, and domain expertise, which all smart grid operators might be unable to afford. Security threats from inadvertently faulty system design or malicious attempts are incredibly likely to be resilient. Blockchains face additional risks due to a lack of expertise with large-scale applications, including problems such as probable failures in the early phases of development. Blockchain ecosystems rely primarily on creating new algorithms, which may be time-consuming and error-prone. Before technology matures, there is still a considerable risk of security breaches, resulting in negative publicity and delayed customer acceptance. Similarly, it requires additional hardware and software to stay updated about sophisticated cyberattacks. Cybersecurity is a complex domain, and protecting oneself is not enough. The security of the entire blockchain ecosystem needs to be ascertained for effective cybersecurity preparedness, which is very difficult to attain from a practical viewpoint. Resilient security architecture and protection from cyberattacks are prominent, and the ability to withstand such attacks is crucial, especially for applications in critical infrastructure such as energy systems. Similarly, as most blockchain designs are Proof of Work (PoW) based, increasing block size might impact throughput adversely. PoW algorithms are more mature and secure but slower and use a lot of energy. Due to the mining, encryption, and decryption delays for large blocks, the consumer might experience significant slowness in blockchain transactions. It can create negative sentiments and a poor service experience for the consumer. Consequently, blockchain developers are attracted to proof-of-stake (PoS) systems that are energy-efficient, faster, and scalable. However, such systems also have a security-decentralisation trade-off. Major challenges in blockchain technology are often related to cost. It has been observed that though blockchain can mitigate other challenges faced by traditional technologies, they are costly to operate. Various types of capital and operational expenditures are incurred for implementing blockchains. Scalability is also affected because it requires eliminating exorbitant costs. Storage, technology, strengthening cybersecurity, and electricity account for most of the cost, which consumers share in exchange for the offered services. Hence, consumers incur additional costs. Moreover, since cryptocurrencies are primarily used to pay for services, the convertibility of such volatile currencies is a considerable challenge. The customer may decide to pay, and situations might arise wherein the available balance is insufficient to pay for the service due to cryptocurrency volatility; however, the opposite is also feasible. Such situations might deter customers from adopting the blockchain. Despite various challenges, blockchain is being widely deployed in smart energy systems. While studying blockchain-based renewable smart energy systems, we identified key operational and transactional challenges. Our review indicates scalability is the critical operational challenge, as highlighted by 11 articles. This result is evident as the expansion of blockchain nodes creates challenges concerning data growth and reduced computing power. The addition of users impacts the performance of various blockchains, particularly public blockchains. As a result, scalability difficulties must be addressed before they can be used on a large scale [32]. While blockchain as a settlement mechanism holds enormous promise for future local energy systems, practical issues such as scalability need to be addressed [83]. There is a definite need to have a regulatory framework to make local energy systems more efficient, encourage community members' participation, and emphasise system implementation. Similarly, regulatory frameworks and standardisation have been identified as other significant challenges. This proposition is supported by nine articles. Standardisation and legal frameworks are essential for seamless technological integration. The lack of frameworks and standardisation creates issues hindering the wide acceptance of advanced technologies such as blockchain. New regulatory frameworks should be devised because traditional policies do not offer energy network innovation and investment incentives. The use of blockchain in the electricity sector should be a priority for policymakers. They should try to grasp the technology, encourage the creation of blockchain standards in the energy industry, and promote innovation by establishing regulatory sandboxes to allow demonstration projects [105]. Apart from the challenges mentioned above, research [79,82,89,99] identifies cybersecurity as another major challenge in the blockchain-based smart energy system. Since modern-day energy distribution systems rely heavily on Information and Communication Technologies (ICT), the requirement for cybersecurity is more evident. Protecting confidentiality, integrity, and availability has been more challenging than ever. In addition, our study [49,52,87] has shown that cost overhead is another roadblock that must be addressed. Blockchain might appear feasible initially; however, network growth, increased customer base, and additional overhead costs remain unforeseen and must be incurred to maintain blockchain-based smart energy systems. Privacy is another severe challenge in blockchain-based smart energy systems. Individual privacy must be ensured, and it must be impossible to ascertain a customer's entire energy cost based on data provided at the community level [67]. The transactive energy system relies on several edge-computing-based energy management systems to make automated decisions. For such systems to work, various internet-of-things-enabled devices must communicate and share information. Privacy issues arise because the time-series data sent through this connection can be exploited to infer private information [29]. Future local power markets are expected to necessitate a comprehensive regulatory framework, particularly regarding data privacy legislation [106]. Interoperability is another challenge identified in our study [38,87]. Blockchain-based applications are rapidly increasing, resulting in many disparate solutions. Due to the vast range of implementations and functionalities, interoperability is a challenge [107]. It has been identified that [76,85] interoperability standards should be created for interaction between different distributed ledger technologies. However [108], higher interoperability, standardisation, and transparency are required to combine dispersed systems and build an integrated collaborative system. Besides operational challenges, our study also identified various transactional challenges in blockchain-based smart energy systems. Throughput has been identified [33,78,79,81,86] as a major transactional challenge. PoW mining has some downsides, including low throughput, high latency, and significant energy consumption, making it unsuitable for many other blockchain applications [109]. Customers' cost overheads due to various scalability mitigations and responding network growth have been identified [49,87,92] as transactional challenges.

6. Conclusions

Blockchain is an emerging technology with potential applications in smart energy systems. This technology is gaining trust with various advanced and secured features such as having no need for a central authority, strong cryptography, and security. This study analysed the applications of blockchain technology in the smart energy domain and identified various operational and transactional challenges. This study emphasised and highlighted several operational and transactional challenges. Thus, several practical issues must be addressed. In particular, identifying these operational and transactional challenges will guide smart energy ventures, academics, investors, start-ups, and policymakers toward a broad understanding of the subject and formulate actionable measures to minimise the risks arising from these challenges. The study introduced the novel technology, its concept, implementation, and use. Later we studied the market distribution of blockchain-based smart energy systems along with a study of the implications with factual detail from various articles. This study analysed operational and transactional challenges in blockchain-based smart renewable energy systems and drew the findings from the identified challenges. During the initial phase, the electric vehicle domain has implemented blockchain; however, other domains have not. The extensive craze of peer-to-peer energy trading is the current market model for transactive energy. With the advancement and fine-tuning of the shortcomings in blockchain technology itself, we can expect new challenges in the future. Future research can include newer blockchain challenges in the smart energy domain, particularly renewable energy sources, and possibly use broad samples and detailed comparative studies. Consequently, there is enough room for future studies to evaluate the quantitative findings concerning utility and satisfaction criteria concerning adopting this novel technology. It concludes that blockchain is still in the research phase and must mature in the smart energy sector. Many benefits can bring a radical shift in the field of renewable energy with this technology. However, applying blockchain in the smart energy domain is among the tougher implementations because various operational and transactional challenges exist. The future research direction is to carry out the Strength, Weakness, Opportunities, and Threat (SWOT) analysis of various blockchain models used in the smart energy sector.

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