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Blockchain Integration and Its Impact on Renewable Energy

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Abstract: This paper investigates the evolving landscape of blockchain technology in renewable energy. The study, based on a Scopus database search on 21 February 2024, reveals a growing trend in scholarly output, predominantly in engineering, energy, and computer science. The diverse range of source types and global contributions, led by China, reflects the interdisciplinary nature of this field. This comprehensive review delves into 33 research papers, examining the integration of blockchain in renewable energy systems, encompassing decentralized power dispatching, certificate trading, alternative energy selection, and management in applications like intelligent transportation systems and microgrids. The papers employ theoretical concepts such as decentralized power dispatching models and permissioned blockchains, utilizing methodologies involving advanced algorithms, consensus mechanisms, and smart contracts to enhance efficiency, security, and transparency. The findings suggest that blockchain integration can reduce costs, increase renewable source utilization, and optimize energy management. Despite these advantages, challenges including uncertainties, privacy concerns, scalability issues, and energy consumption are identified, alongside legal and regulatory compliance and market acceptance hurdles. Overcoming resistance to change and building trust in blockchain-based systems are crucial for successful adoption, emphasizing the need for collaborative efforts among industry stakeholders, regulators, and technology developers to unlock the full potential of blockchains in renewable energy integration.

Keywords: blockchain; renewable energy; global collaboration; energy optimization; renewable source utilization; privacy concerns

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1. Introduction

Natural resources that replenish over time, such as sunlight, wind, rain, and geothermal heat, are the source of renewable energy [1,2]. Compared to conventional fossil fuels, it is seen as a sustainable and environmentally beneficial substitute [3]. Renewable energy can meet global energy demands while lowering greenhouse gas emissions and enhancing air quality [4,5].

However, several concerns and obstacles have made the adoption of renewable energy more difficult. The intermittent nature of renewable energy sources, which can cause variations in the supply and demand of energy, is one of the primary obstacles [6,7]. This problem has been solved by the development of energy storage technologies, including batteries and pumped hydro storage [8,9].

The high price of renewable energy technology in comparison to conventional fossil fuels is another problem. This has been addressed by government subsidies and incentives, in addition to technological improvements that have resulted in cost savings [10,11].

The adoption of renewable energy is still fraught with problems despite these remedies. The absence of a centralized system for monitoring and validating the production and use of renewable energy is one of the major obstacles [12]. Fraud and double-counting of renewable energy credits have resulted from this. Blockchain technology has been suggested as a solution to these problems, because it offers a transparent and decentralized mechanism for tracking and validating the generation and use of renewable energy [13–15].

Blockchain is a distributed ledger technology that eliminates the need for middlemen and enables safe and transparent transactions. It offers a transparent and safe mechanism for monitoring and validating the production and use of renewable energy, which has the potential to completely transform the renewable energy sector. This can contribute to a rise in confidence and trust in the markets for renewable energy [16–19]. Blockchain technology enables decentralized smart grids using DERs like solar panels and windmills. Its platforms make energy trading reliable, allowing DERs to sell excess energy efficiently. Smart contracts automate buy/sell energy agreements, reducing transaction costs and settlement times [20,21]. Blockchain records and tracks energy data on a public ledger, reducing exploitation risks and improving sector transparency in gas and energy commodity trading [12,22].

Taking into account the body of literature, earlier evaluations together offer a grasp of the situation and difficulties surrounding the integration of blockchain technology with renewable energy systems. While Nepal et al. [23] explored the operational and transactional problems in smart renewable energy systems, Henninger and Mashatan [24] provided insights into the technology layers of grid system infrastructures and suggested a future state employing blockchain. Gavusu et al. [18] drew attention to the importance of blockchain integration in the renewable energy sector, whereas Barcelo et al. [25] discussed the necessity for regulatory development and how to overcome the difficulties that come with implementing blockchain technology. The bibliometric study of Cui et al. [26] revealed prospective trends in the energy internet, management, systems, and trading, as well as research gaps in blockchain-based renewable energy applications, technology, and policy.

Although operational, transactional, and technological challenges—as well as the significance of regulatory development—have been emphasized in previous works, our paper seeks to fill these gaps in the literature with a more detailed analysis and practical suggestions. This review paper examines blockchain-based power management, renewable energy trading, investment platforms, decentralized energy systems, and technology integration to fill gaps in the literature. The analysis offers practical advice for integrating blockchain technology with renewable energy systems.

This paper is structured into multiple important sections. A discussion of the main ideas is followed by the methodology and conclusions, which shed light on the function of blockchain technology in decentralized systems, energy trading, investment platforms, power management, and technology integration. The discussion synthesizes findings, future directions that suggest additional research, and the conclusion highlights the important points.

2. Key Concepts in Renewable Energy

2.1. Energetic Community

Energy communities are groups whose mission is to promote or assist the efficient use of energy, to facilitate the collective purchase of renewable energy or technology, or to supply energy that is generated from renewable sources. The primary goal of renewable energy communities should not be financial gain, but rather the provision of environmental, economic, or social benefits to their members, shareholders, or the communities in which they operate [27].

Environmental and climate change worries appear to be the primary drivers of membership in these groups. Any renewable energy project's development in these communities also depends heavily on trust [28].

Energy communities can reach more people of all ages, genders, socioeconomic backgrounds, and educational levels if enabling policies are in place [29]. In addition to being active consumers of energy, members of energy communities can take part in a variety of roles within the energy market, such as determining the type and level of energy production. Citizens' buy-in and support are crucial for the energy transition wave to succeed. Community energy projects are a relatively new "emergent phenomenon" that gives people a chance to become involved in the energy market and their local community at large [30].

Energy communities can improve security, expedite energy trading, and enable peer-to-peer energy transactions by utilizing blockchain technology. The incorporation of blockchain technology in the energy community is consistent with the wider practice of employing cutting-edge technologies to enhance energy systems and advance sustainability [31].

To store and track information about the energy footprint of public buildings and communities, Galici et al. [32] suggested using blockchain as an energy-open data ledger. Through blockchain-enabled smart meters, the developed platform made it possible to record energy production and consumption, promoting transparency for research and audits. It also made it easier to track sustainability and advance public infrastructure improvement initiatives.

Peer-to-peer energy trading, in which prosumers trade renewable energy directly with consumers in their vicinity, is a method used by smart grid transactive energy management. The proposal of a Decentralized and Transparent peer-to-peer Energy Trading (DT-P2PET) scheme, which uses blockchain technology to address security and scalability issues with current P2P approaches, has resulted in increased efficiency and profitability for both parties [33]. Peer-to-peer, community self-consumption, and transactive energy are just a few of the novel market models that Montakhabi et al. [34] investigated for how blockchain could change urban energy trading. Dissecting these models and their implications, clarified the dynamics of governance, market democratization, and investment requirements, providing a new angle on blockchain's function in energy transition governance.

2.2. Decentralized Energy Production

Decentralized energy production pertains to the generation of power near its consumption sites, as opposed to relying on a central facility situated at a considerable distance. By integrating heat and power, this methodology enhances the efficiency of renewable energy utilization, minimizes reliance on fossil fuels, and improves environmental impact [35]. Decentralized energy systems can incorporate a wide variety of energy sources, including intermittently producing renewable sources like wind and solar [36]. Local generation mitigates transmission losses and carbon emissions while enhancing supply security for all customers. This is achieved by preventing the reliance on a single limited supply or a relatively small number of large power facilities [35].

Decentralization within the realm of distributed energy services has the potential to yield cost-effective products and services, as well as facilitate the development of service process modules that generate value for both the organization and its clientele [37–39]. The construction of sustainable energy systems is dependent on accurate and dependable data, as such data facilitates decisions regarding the management and investment in infrastructure and technology. Furthermore, this data may assist in surmounting market defects [35]. The planning flexibility of distributed generation projects is attributed to their compact dimensions and abbreviated construction schedules, in contrast to more sizable central power plants. Energy efficiency initiatives could benefit from a decentralized energy system. Smart meters that provide more data on energy flows may encourage consumers to be more mindful of their consumption. Energy consumers become producers and have a greater economic interest in efficient production and consumption via on-site energy production [40,41].

Nevertheless, the energy sector encounters various challenges and concerns when it comes to the digitization of distributed energy services and operations. Concerns such as the necessity to establish a standardized framework for interconnection requirements to mitigate the technical and legal complexities linked to supplying electricity to the grid, as well as the development of capabilities and expertise to equip a proficient workforce capable of operating and maintaining decentralized generation, storage, and distribution systems, are among these [35]. Investigating the limitations and capabilities of decentralized energy production systems in urban settings, an experiment was undertaken to determine their potential and constraints [42]. Distributed renewable energy (DRE) has emerged as the most auspicious paradigm for universal access to sustainable energy. Decentralized energy systems have been proposed as a potential complement to centralized systems [43].

2.3. Energy Trading

The decentralized architecture of blockchain technology presents prospects for a paradigm shift in the domain of renewable energy trading [44]. This nascent methodology tackles significant obstacles linked to conventional energy systems, such as their dependence on centralized control frameworks and susceptibilities concerning data governance and security.

There has been a surge in recent interest regarding the investigation of how blockchain technology might augment the sustainability and efficacy of energy trading. Extensive research has been devoted to the development of mechanisms and platforms that enable direct exchanges between energy producers and consumers. These advancements aim to streamline the energy ecosystem, decrease expenses, and foster increased adaptability [26,45].

A tamper-proof, secure, and transparent ledger system, blockchain enables the monitoring of energy transactions in real time. The decentralized nature of this system obviates the necessity for intermediaries, resulting in reduced transaction fees and enhanced confidence between purchasers and vendors [45].

A noteworthy advancement in energy trading enabled by blockchain technology is peer-to-peer (P2P) exchanges. Through these exchanges, small businesses and individuals can purchase and sell excess energy produced by renewable sources such as rooftop solar panels. Local in nature, these transactions frequently transpire beyond the purview of conventional utility corporations [46].

The utilization of machine learning algorithms and artificial intelligence methods is being implemented to enhance the efficiency and precision of energy trading procedures, all the while reducing operational uncertainties [46–48].

Notwithstanding the myriad advantages that blockchain technology presents, it is not without its constraints, including but not limited to sluggish transaction processing times, elevated energy consumption during mining operations, and restricted scalability. However, continuous research endeavors to surmount these challenges, thereby enhancing the feasibility and availability of energy trading facilitated by blockchain technology [43].

2.4. Grid Management

Blockchain technology offers novel prospects for enhancing the administration and functioning of contemporary electrical infrastructures, colloquially referred to as smart grids. By capitalizing on the intrinsic attributes of blockchain technology, intelligent platforms can be fortified, preserved, and rendered more effective [49,50].

Decentralized governance models are made possible by blockchain technology, enabling multiple parties to administer the grid collaboratively while retaining individual autonomy [51,52]. This methodology promotes enhanced confidence and collaboration among various parties involved, such as utilities, regulators, and end-users.

The implementation of cryptographic techniques within blockchain technology enables the secure exchange and management of sensitive data, thereby safeguarding user privacy and ensuring adherence to regulatory requirements [53,54]. Additionally, blockchain technology reduces fraudulent activities and enables transparent surveillance of grid performance by providing a tamper-proof audit trail. Blockchain technology enables the establishment of instantaneous energy markets, granting prosumers (consumers and producers) the ability to exchange electricity directly with one another. This not only improves market flexibility, but also fosters the adoption of renewable energy sources [51,52].

The grid can autonomously adjust supply in response to fluctuating demand using blockchain technology, thereby minimizing waste and optimizing resource utilization [55,56]. In addition, systems facilitated by blockchain technology can authenticate grid components, thereby preventing forgery and ensuring safety. The zero-trust architecture of blockchain enhances the cybersecurity stance of smart grids by safeguarding critical infrastructure and providing protection against malevolent attacks [57].

Notwithstanding the manifold benefits that blockchain technology presents, its extensive implementation encounters substantial obstacles, most notably in the domains of interoperability, standardization, and regulation [51,52]. However, continuous research and development endeavors are focused on surmounting these challenges to establish a more equitable, secure, and efficient energy ecosystem.

2.5. Environmental Impact

There have been environmental repercussions associated with blockchain technology, specifically regarding energy consumption and carbon emissions. The energy consumption associated with cryptocurrency mining has garnered considerable attention in recent years, but there is a scarcity of literature that evaluates the environmental impacts of cryptocurrency mining and transactions [58]. Comparable to the energy consumption of entire nations, Bitcoin mining has been associated with climate change and human mortality via its carbon footprint [59].

Nevertheless, recent policy interventions have been implemented to mitigate the carbon emissions, mortality, and net-zero consequences associated with non-fungible tokens and Bitcoin [59]. Several scholars have put forth the notion of green blockchain, an application of blockchain technology that aims to mitigate environmental harm and advance sustainability [60].

Carbon emissions and energy consumption are not the only environmental consequences of blockchain technology. The social impacts of blockchain technology include the possibility that social inequalities and the digital divide will be exacerbated [61].

Globally, there have been demands for immediate action to mitigate the environmental impact associated with Bitcoin mining. The results of a multi-attribute assessment of the environmental challenges and impacts associated with Bitcoin mining activities on a global scale indicate that immediate action is required to reduce Bitcoin mining's environmental footprint [62].

3. Methodology and Analysis of the Current State

This review attempts to offer an extensive overview of how blockchain technology can be integrated into renewable energy systems. It aims to provide practical recommendations for successful implementation by addressing specific gaps identified in the literature.

The methodology for this review involved a systematic search and selection process to identify relevant articles on the integration of blockchain technology in renewable energy. The search was conducted in February 2024, utilizing the Scopus database. The search query focused on identifying articles with the keywords "blockchain" and "renewable energy" in the title field. Initially, 82 results were retrieved from the search. These results underwent an initial analysis to determine their relevance to the review topic.

This article was improved by using advanced language processing AI tools. Grammarly, known for its advanced grammar and style suggestions, improved content clarity and coherence. QuillBot's AI paraphrasing tool also improved our written communication quality and diversity.

3.1. Current State

The integration of blockchain technology into the renewable energy sector has attracted considerable interest in recent times, creating an interdisciplinary environment that merges sustainability, innovation, and technology. The present analysis examines four primary aspects: the temporal progression of publication trends, the distribution of scholarly contributions across subject areas, the preferences for source types, and their geographical origins. Through a careful examination of these aspects, our objective is to decipher the dynamic storyline surrounding the incorporation of blockchain technology into the renewable energy sector. This will be achieved by emphasizing the worldwide cooperation, methods of distribution, and interdisciplinary character of this domain.

An examination of articles according to the years of their publication demonstrates a dynamic progression in the investigation of blockchain integration within the renewable energy sector (Figure 1). A pivotal stage becomes apparent in 2018 and 2019, signifying the initial acknowledgment of the potential of blockchain technology to tackle obstacles in the renewable energy sector. The years that follow, specifically 2020 to 2023, exhibit a discernible upward trajectory in research productivity, underscoring the escalating curiosity and investigation within this domain. The 2020 decline could potentially be ascribed to the worldwide upheavals resulting from the COVID-19 pandemic, which impacted the priorities of research. The resurgence observed in 2021 and 2022 indicates a possible shift in emphasis, which could be attributed to technological progress, policy changes, and increased industry acceptance. The scarcity of articles in 2024 could potentially signify the progression of research and the introduction of innovative perspectives.

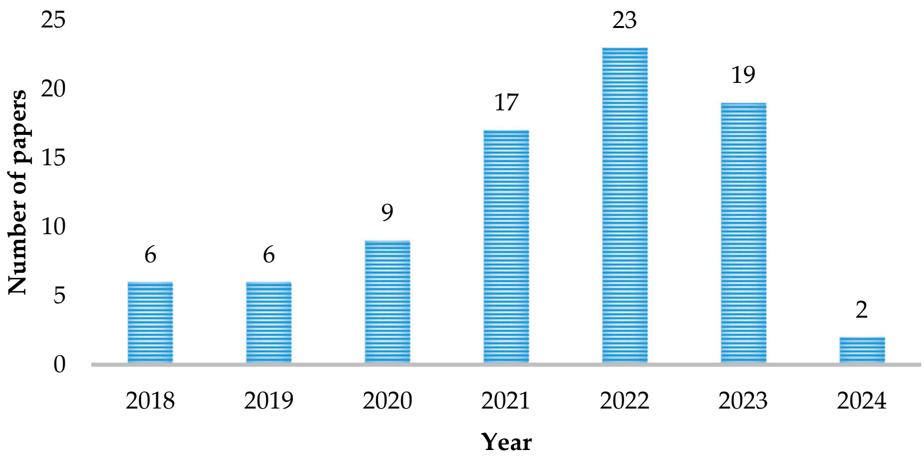

Figure 1. Number of articles by publication year.

The analysis reveals a diverse distribution of articles across subject areas in the exploration of blockchain integration in renewable energy (Table 1). Engineering claims the majority with 37 articles, emphasizing technical implementation. Energy closely follows with 35 articles, focusing on practical applications. Computer Science, a critical player, contributes 33 articles, reflecting a strong emphasis on technological solutions. Mathematics and Decision Sciences offer quantitative and strategic perspectives with 12 and 11 articles, respectively. Environmental Science and Business Management address ecological and managerial aspects, each with 11 and 10 articles. Economics, Econometrics, and Finance delve into economic implications with 7 articles. Earth and Planetary Sciences, Materials Science, and Social Sciences contribute 6, 6, and 5 articles, respectively. Physics and Astronomy represent 2 articles, while Chemical Engineering and Medicine are niche areas with 1 article each.

The analysis of 82 articles reveals a diverse distribution in source types (Figure 2). Journals lead with 41 articles, emphasizing rigorous peer-reviewed exploration. Conference proceedings follow closely with 32 articles, highlighting dynamic research platforms. Six articles are from books, offering in-depth analyses, while three belong to book series, indicating a thematic approach. This varied distribution showcases a multifaceted dissemination strategy, leveraging journals for comprehensive insights, conferences for timely discussions, and books for authoritative resources, contributing to a nuanced understanding of blockchain integration in renewable energy.

Table 1. Subject area of the papers.

Field	Number of Papers
Engineering	37
Energy	35
Computer Science	33
Mathematics	12
Decision Sciences	11
Environmental Science	11
Business, Management and Accounting	10
Economics, Econometrics and Finance	7
Earth and Planetary Sciences	6
Materials Science	6
Social Sciences	5
Physics and Astronomy	2
Chemical Engineering	1
Medicine	1

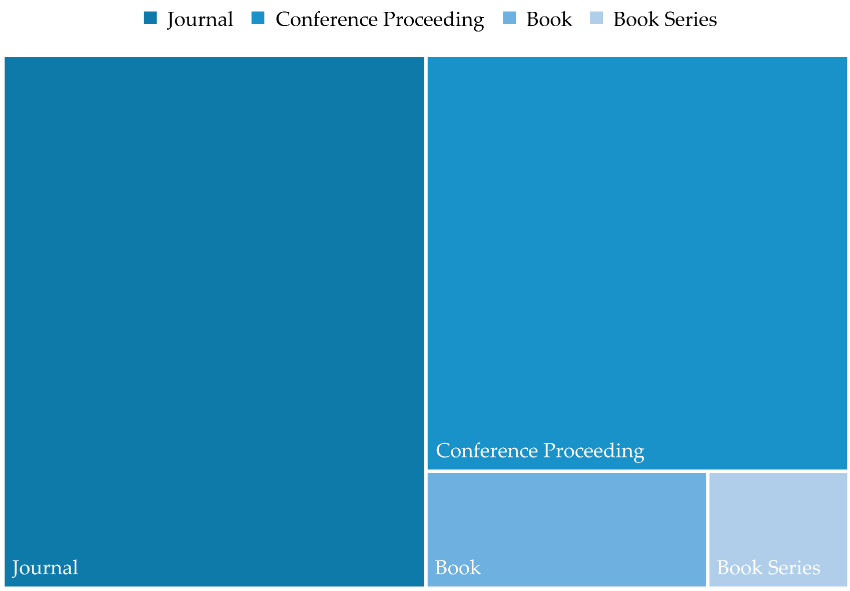

Figure 2. Source type distribution.

The distribution of research articles across different countries provides insights into the global engagement with the intersection of blockchain technology and renewable energy (Figure 3). China emerges as the leading contributor, with 26 articles, underscoring its prominent role in advancing research in this field. The United States follows with 10 articles, reflecting a significant presence in exploring the synergy between blockchain and renewable energy. India, Canada, Iran, and Thailand each contribute substantively, indicating a diverse set of countries actively involved in this interdisciplinary research. Notably, Australia, Indonesia, South Korea, and Sweden also demonstrate considerable engagement with multiple articles. The widespread geographical representation across countries like Turkey, Austria, Brazil, Croatia, and Denmark signifies a global collaborative effort to understand and harness the potential of blockchain in the renewable energy landscape.

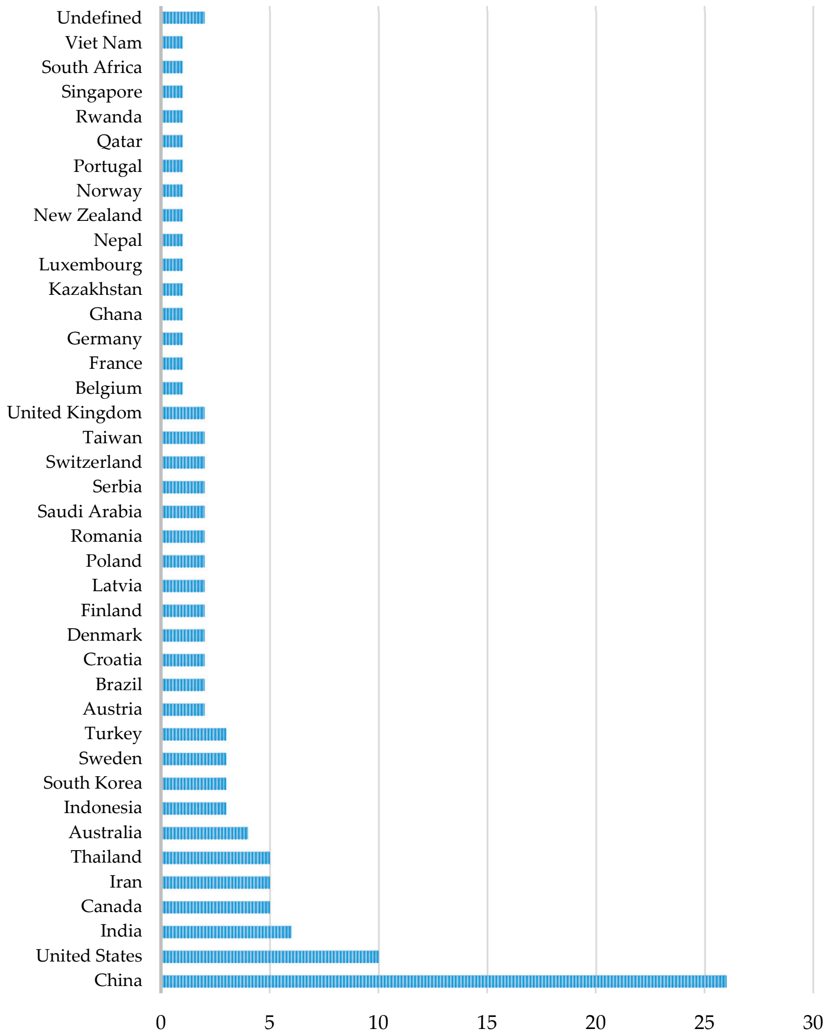

Figure 3. Country distribution.

3.2. Paper Selection

Following this analysis, screening criteria were applied to refine the results. Specifically, only journal articles written in English were considered for inclusion, while other document types such as reviews, conference papers, book series, and book chapters were excluded.

After applying the screening criteria, 36 articles remained for further consideration. These articles underwent a more detailed examination based on their title and abstract to assess their suitability for inclusion in the review. A total of 33 articles were selected based on their relevance to the topic of blockchain integration in renewable energy.

The final selection of articles represents a comprehensive review of the current literature on the subject, providing valuable insights into the various applications, challenges, and impacts of blockchain technology in the renewable energy sector.

3.3. Limitations of the Review

Systematic reviews may have biases and limitations. Searching titles for keywords may exclude relevant literature. Scopus alone may miss relevant articles in other databases. Title and abstract screening and single-day searches may bias the selection and timeframe.

4. Findings

The selected works (33 articles) demonstrate the various uses and viewpoints of blockchain integration in the renewable energy sector. One noteworthy strategy is the creation of a decentralized power dispatching model using blockchain technology for grids with flexible loads and renewable energy sources to increase efficiency and reliability [63]. Furthermore, the research looks into blockchain-enabled solutions for the adoption of blockchains in the renewable energy supply chain, investment decision-making in green blockchain investments, and the transparent and secure trading of renewable energy certificates [64–67]. Together, these initiatives highlight how blockchain technology can completely transform the management of renewable energy sources, guaranteeing efficiency, security, and transparency in all areas of the sector.

Further uses of blockchain technology include tracking standards-compliant renewable energy power, blockchain-enabled vehicle-to-vehicle energy trading, and blockchain-based renewable energy trading systems (Table 1) [68–70]. These use cases demonstrate how flexible blockchain technology can be in strengthening the resilience of the electrical grid, encouraging sustainable growth, and supporting decentralized energy systems. Blockchain is positioned as a catalyst for positive change in the renewable energy landscape, covering issues related to supply chain management, privacy-preserving certificate trading, and green investment decision-making. This lays the groundwork for a future where energy is more secure, transparent, and efficient. Table 2 presents blockchain integration in renewable energy.

Table 2. Blockchain integration in renewable energy: application categories.

Number	Study	Cited by	Power Management	Renewable Energy Trading	Investment and Management Platforms	Decentralized Energy Systems	Technology Development and Integration
1	[63]	0	✔				
2	[65]	2		✔			
3	[64]	55				✔	✔
4	[66]	36				✔	
5	[67]	8	✔				
6	[71]	15		✔			
7	[72]	35			✔		
8	[73]	0		✔			
9	[74]	2	✔				
10	[68]	1	✔				
11	[69]	2			✔		
12	[75]	7		✔			
13	[76]	0		✔			
14	[77]	40	✔				✔
15	[78]	45		✔			
16	[79]	1		✔			✔
17	[80]	2					✔
18	[81]	35		✔			
19	[82]	2					✔
20	[83]	19					✔
21	[84]	7				✔	
22	[70]	9					✔
23	[85]	15		✔			✔
24	[86]	41	✔				
25	[87]	8		✔			
26	[88]	0			✔		✔
27	[89]	1			✔		
28	[90]	3		✔			✔
29	[91]	3					✔
30	[16]	82	✔		✔		
31	[14]	43				✔	
32	[17]	22			✔		✔
33	[92]	0	✔				✔

4.1. Blockchain-Based Power Management

Blockchains overcome concerns of uncertainty, privacy, and security in a decentralized power dispatching paradigm presented by Xu et al. [63] by introducing smart contracts and an enhanced PoW-GAD consensus algorithm. This approach improves wind and photovoltaic energy usage, while simultaneously lowering system costs. The study highlighted how blockchain technology can be used to build a more robust and dependable electricity dispatching system.

Furthermore, Zhao et al. [67] investigated the use of blockchain in intelligent transportation systems. This research focused on using blockchain validation and energy demand analysis to create an efficient renewable energy management mechanism for electric vehicles (EVs). The use of a blockchain-based strategy reduces fuel waste, improves system performance overall, and guarantees safe energy transfer inside the grid. Furthermore, Liu et al. [71] suggested integrating blockchain technology into a market for electricity with minimal carbon emissions and precisely quantified the uncertainty associated with wind power generation. With the help of this blockchain-based approach, electric vehicle owners and wind power providers may interact more profitably, reducing charging expenses and boosting net earnings.

Moreover, blockchain technology has promise for systems that handle investments in green energy. Werapun et al. [69] presented a decentralized platform for sustainable development that manages equity-sharing investment schemes for photovoltaic projects using blockchain technology. In comparison to centralized systems, this platform uses blockchain technology to divide income from electricity generation reliably and economically. Xu et al. [86] suggested a reliable energy-dispatching method for highly renewable energy-penetrated power networks. This method balances the electricity, makes efficient use of renewable energy sources, and guarantees transparent record-keeping via blockchains using smart contracts and consensus algorithms.

4.2. Renewable Energy Trading

Several articles explored several facets of blockchain-enabled trading in renewable energy. In a noteworthy study, a hybrid permissioned blockchain-based Renewable Energy Certificate (REC) trading system with continuous double auction rules to optimize pricing mechanisms, guarantee fair transactions, and maximize revenue for buyers and sellers was proposed by Wang et al. [65]. Utilizing information entropy theory to measure uncertainty in wind power producer transactions, another study by Liu et al. [71] presented the idea of uncertainty cost in day-ahead markets. To ensure a balanced supply and demand of electricity, a blockchain network is set up to enable effective and safe trading between wind power providers and electric vehicles (EVs) [71].

The development of a decentralized platform for REC issuance and trading demonstrated the importance of tokenization and traceability in the world of REC trading. By utilizing blockchain technology, this effort seeks to lower operational costs, improve transaction efficiency, and offer a safe method for the issuing, verification, and retirement of RECs [75]. Furthermore, an investigation into a trading system for renewable energy assets delves into the development of a blockchain-based framework, delineating the parties involved in transactions, associated protocols, regulations, and technological enablers [82]. Through efficient and safe blockchain-based trade, the goal is to encourage cooperation in the new energy system and make it easier for green energy assets to be circulated [16].

Optimizing energy use is important when trading renewable energy, especially when it comes to electric vehicles (EVs). An incentive program for electric vehicles (EVs) based on blockchain technology was presented by Chen et al. [77] to address this issue. Based on their driving and charging habits, the system assigned EV drivers a higher priority, advising users to charge during times when Renewable Energy (RE) generation is at its peak. Additionally, dynamic energy management approaches for distributed energy systems with high penetration of renewable energy were the emphasis. By integrating blockchain technology, these systems will function more efficiently and provide efficient energy trade with less network latency [92].

Research by Lei et al. [74] that presented an energy trading platform built on a permissioned blockchain explores the environment of trading renewable energy microgrids. To improve affordable and effective trading of renewable energy, this platform used automated trading procedures, such as token trading methods and account management. Additionally, homomorphic encryption was incorporated to protect user privacy.

4.3. Investment and Management Platforms

In the realm of Investment and Management Platforms within the renewable energy sector, three distinctive articles offered insights into navigating green blockchain investments and enhancing sustainable development. Liu et al. [64] conducted a comprehensive two-phase analysis. Initially, utilizing IT2 fuzzy decision-making methodologies, the study prioritized criteria like continuity in energy supply and legal conditions for effective decision-making. In the subsequent phase, the article employed the IT2 fuzzy VIšeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) approach to rank five renewable energy alternatives, ultimately highlighting wind and solar energy as the most fitting choices for blockchain technology integration.

Werapun et al. [69] introduced a groundbreaking platform for managing renewable energy investments. Leveraging blockchain technology, particularly the Ethereum blockchain and smart contracts, the platform enabled the decentralized handling of equity-sharing investment programs for solar PV projects. Successfully tested with solar-PV electricity generation data, the platform demonstrated efficiency in handling transactions and offered cost-effective alternatives compared to centralized solutions. Zuo [75] proposed a decentralized platform for tokenizing Renewable Energy Certificates (RECs). This blockchain-based solution aimed to enhance traceability, and transparency, and reduce operational costs in REC exchanges. By representing RECs as blockchain tokens, the platform ensured trustworthy information recording, tracking, and verification, demonstrating the potential for low costs, transparency, and user-friendly REC transactions.

4.4. Decentralized Energy Systems

A revolutionary change in energy resource management is embodied by decentralized energy systems, which often incorporate blockchain technology for increased security, efficiency, and transparency. Sahebi et al. [66] conducted a noteworthy study that explores the integration of blockchain technology in the renewable energy supply chain. The research identifies and assesses problems using a hybrid approach that incorporates gray numbers. "High investment cost" emerges as a key hurdle. This emphasizes how critical it is to remove barriers preventing blockchain technologies from integrating smoothly into decentralized renewable energy systems.

A paper by Wang et al. [68] took a different tack, emphasizing how blockchain-enabled vehicle-to-vehicle (V2V) energy trading might strengthen power grid resiliency. This research introduced cryptographic EV leader election and sharding strategies to improve scalability, and it proposed the BAC-SDS consensus mechanism. The study, which uses Hyperledger Fabric as its implementation, shows that V2V Energy Trading is more resilient than typical centralized methods. The security, throughput, and scalability of the proposed consensus method are exceptional, highlighting the critical role that decentralization plays in bolstering the resilience of the electrical system. Furthermore, a thorough blockchain-based architecture for Distributed Renewable Energy Management Systems (DREMS) was described in another study by Alsunaidi and Khan [82]. This study presented specific protocols inside the blockchain architecture and identified installation strategies for renewable energy (RE) systems. The study evaluated the suggested protocols' suitability for fulfilling the determined DREMS requirements by contrasting them. These articles highlighted the potential of decentralized energy systems and how blockchain technology may be used to overcome obstacles and maximize efficiency in the administration of renewable energy sources.

4.5. Technology Development and Integration

The papers in this area focused on the use of blockchain technology in renewable energy while highlighting technological advancements and their smooth integration into current frameworks. The study by Liu et al. [64], which used the IT2F DEMATEL-ANP (DANP) technique, emphasized the importance of legal circumstances and a steady supply of energy in green blockchain investments. It also called attention to the selection of renewable sources for sustainable blockchain technology and the enforcement of legal requirements. In the meantime, Almutairi et al. [72] modeled factors that facilitate the use of blockchain technology in supply chains for renewable energy, citing obstacles such as "high investment cost" as a significant barrier and promoting affordable blockchain integration.

Going beyond simple modeling, Safari et al. [79] combined blockchain, P2P trading, LSTM networks, and decision trees to present an innovative predictive model for energy prices in decentralized marketplaces. This model—called DeepResTrade—shows impressive predictive accuracy when it comes to energy pricing. Yamaguchi et al. [80] examined how blockchain was used in Brazil for renewable energy certifications, using case study methods and designed science research to examine how technological adoption and organizational positioning affect sustainability. According to Indonesian rules, Husin et al. [89] investigated the renovation costs based on Green Building assessment utilizing Blockchain-BIM, indicating improved cost performance in contemporary retail center structures.

Analyzing the relationship between green and non-green cryptocurrency indices and green bond indices, Erdogan and Ahmed [58] explored the larger influence of blockchain on renewable energy resources and suggested developing green cryptocurrencies and integrating them with digital green financing. To address integration issues, Yildizbasi [16] suggested a novel integration process and outlined benefits for energy policymakers. He also examined the impact of the circular economy era on blockchain integration with renewable energy systems. In an attempt to evaluate the Hyper Delegation Proof of Randomness (HDPoR) algorithm for blockchain, Huh and Kim [14] introduced a novel blockchain consensus method, highlighting its potential for effective and safe P2P transaction service models in new and sustainable energy systems. Alaguraj and Kathirvel [92] described a cutting-edge smart grid system that combines blockchain technology with IoT for renewable energy, improving transaction throughput, latency, data integrity, privacy compliance, and resilience against cyberattacks.

5. Discussion

Blockchain technology, known for its decentralized and tamper-resistant nature, has increasingly become a focal point in reshaping the renewable energy landscape. As the world grapples with the challenges of climate change, there is a growing need for innovative solutions to optimize the generation, distribution, and trading of renewable energy. Blockchain's ability to provide a transparent, secure, and decentralized ledger system has led to a surge in research and development initiatives aimed at harnessing its potential in the renewable energy sector.

Within this context, researchers and industry experts are exploring various techniques and methods to leverage blockchain in addressing key issues in renewable energy transactions. One prominent theme revolves around the utilization of advanced consensus algorithms to enhance the efficiency, security, and scalability of blockchain systems in managing renewable energy transactions. For instance, the introduction of the PoW-GAD consensus algorithm in a blockchain-based decentralized power dispatching model highlights a commitment to addressing uncertainty and optimizing power dispatching [63]. Similarly, the exploration of BAC-SDS consensus for vehicle-to-vehicle energy trading demonstrates a focus on cryptographic techniques and sharding for achieving superior security, throughput, and scalability in decentralized energy transactions [68].

Smart contracts play a pivotal role in implementing automated and trustless processes within blockchain-enabled renewable energy systems. These self-executing contracts are a common thread in various studies, ensuring transparent and secure execution of agreements without the need for intermediaries. The integration of smart contracts is particularly evident in models like the blockchain-based renewable energy power tracking method, where the entire lifecycle of renewable energy is covered by a smart contract on the Ethereum blockchain [74]. This approach not only streamlines processes, but also promotes accountability and reliability in renewable energy transactions.

Privacy and security concerns are critical considerations in the development of blockchain solutions for renewable energy. Techniques addressing these concerns, such as the use of information entropy theory in a blockchain-based renewable energy trading model, highlight a dedication to preserving privacy and security in transactions involving renewable energy assets [71]. Moreover, the incorporation of cybersecurity perspectives in studies like the evaluation of blockchain technology strategies underscores the need for robust security measures to safeguard against cyber threats and ensure the integrity of renewable energy systems [88].

These studies incorporate simulation and experimental validation as crucial elements, which serve to illustrate the practicality and efficacy of the techniques that are being proposed. The experimental validation of an innovative market settlement mechanism based on blockchain technology or the simulation confirmation of a decentralized power dispatching model based on blockchain technology both enhance the credibility and practical viability of blockchain implementations in the renewable energy sector. Together, the prioritization of global perspectives, the incorporation of IoT, and the resolution of obstacles like substantial investment expenses emphasize a dedication to improving methodologies and approaches that may fundamentally transform the domain of renewable energy administration via blockchain technology.

The integration of blockchain technology into the renewable energy sector offers a multitude of prospects; however, it also entails a collection of obstacles and constraints that need to be surmounted to ensure a prosperous deployment. A significant obstacle is the inherent unpredictability of power dispatching systems, specifically regarding effectively managing the ever-changing characteristics of renewable energy sources such as solar and wind. Furthermore, the transparency inherent in blockchain technology gives rise to privacy concerns, which require meticulous handling of sensitive information to safeguard user privacy and adhere to regulatory requirements [73]. Additionally, it is critical to prioritize the protection of the renewable energy infrastructure's integrity by assuring security against potential vulnerabilities and cyber threats.

An additional obstacle that blockchain networks encounter is scalability, which pertains to the efficient management of an expanding quantity of transactions, particularly in the context of trading renewable energy [81]. Certain consensus mechanisms, such as proof-of-work, are energy-intensive, which gives rise to apprehensions regarding their operational expenses and ecological repercussions, which may compromise the integrity of the network. In addition, operational challenges arise from the intricacy of integrating blockchain technology into the trading of renewable energy certificates; these must be surmounted by stakeholders to guarantee a smooth transition and functioning of the system [65].

Ensuring adherence to established energy regulations and adjusting to evolving legal frameworks governing blockchain technology are both imperative for legal and regulatory compliance, which is a critical factor to be taken into account [17]. Furthermore, there are technical obstacles to consider when integrating blockchain technology into pre-existing energy infrastructure. One such obstacle is ensuring interoperability between various blockchain platforms and legacy systems [82]. The widespread adoption of blockchain-based solutions for energy management systems may be impeded by the need to surmount resistance to change that arises from traditional systems [16]. Furthermore, it is critical to establish confidence among market participants and stakeholders in blockchain-based systems. This necessitates endeavors in education and awareness campaigns to surmount doubts and guarantee adoption [17].

Although blockchain integration in renewable energy has made significant progress, there are still several voids in the literature that offer potential avenues for future research. An aspect worthy of consideration is the investigation into more sophisticated consensus mechanisms than the conventional proof-of-work or proof-of-stake. These mechanisms strive to achieve environmental sustainability, energy efficiency, and scalability improvements. Furthermore, it is imperative to conduct thorough examinations regarding the establishment of interoperability standards. Such standards would enable smooth communication among various blockchain platforms and improve the integration of renewable energy systems. Further investigation is warranted regarding the possible integration of blockchain technology with nascent technologies, including artificial intelligence and machine learning, to enhance the efficiency of decision-making procedures about the administration of renewable energy.

With the increasing adoption of blockchain technology in the renewable energy industry, policymakers and regulatory bodies are compelled to construct all-encompassing frameworks that tackle the distinct obstacles and prospects that arise from its deployment. Subsequent investigations ought to concentrate on the formulation and assessment of policy strategies that foster the integration of blockchain technology while concurrently guaranteeing adherence to established energy regulations. Furthermore, it is imperative to comprehend the regulatory obstacles to data privacy, security, and smart contracts as they pertain to blockchain applications in the renewable energy sector. Such knowledge is vital for fostering an atmosphere that is conducive to innovation.

The economic and social ramifications of integrating blockchain technology into the renewable energy sector are intricate and diverse. Further investigation is warranted to explore the socio-economic ramifications of decentralized energy management systems. This should encompass community engagement, the potential to alleviate energy poverty, and the democratization of energy. Furthermore, it is critical to comprehend the skill prerequisites and potential for job creation that arise from the extensive implementation of blockchain technology in the renewable energy industry. This knowledge is vital for formulating well-informed policy strategies and developing the appropriate workforce. An investigation into the social reception and perception of blockchain-driven solutions within the renewable energy sector may yield significant knowledge regarding the promotion of public confidence and adoption.

6. Future Directions

Strong governance models are required, as the energy sector uses blockchain technology to guarantee that all transactions are just, transparent, and accountable. Future research aiming at enhancing the efficiency and reliability of energy trading may concentrate on decentralized autonomous organizations (DAOs), smart contract-based governance mechanisms, or decentralized governance structures. It is urgent to address worries regarding the power consumption of blockchain networks and their long-term viability.

Transitioning to renewable energy has been hampered by several factors, including high initial costs, social and political resistance, and technological limitations. However, there are advantages, like generating revenue, jobs, and environmental sustainability. The distributed ledger and peer-to-peer transactions of blockchain technology could soon make powerful and open energy markets a reality. It may also make it easier to include renewable energy sources. If blockchain technology is to aid in the shift to sustainable energy, it must address issues with scalability, technical complexity, and security risks. Legislative changes that encourage the use of renewable energy sources and financial support for them are significant facilitators.

The incorporation of blockchain technology into renewable energy sources, public adaptability, and skill development are all hampered by uncertainties regarding behavioral change. To guarantee the broad implementation of peer-to-peer energy trading platforms, prosumer awareness regarding the significance of enhancing trust in renewable energy must be increased. According to the theory of green marketing, blockchain technology's immutability, transparency, and certificates of origin can greatly increase consumer trust in renewable energy sources.

Further research is needed in this area, because blockchain platforms are currently unable to handle the volume of transactions necessary for large-scale energy trading. Efforts to improve consensus processes or Layer 2 solutions could be the main focus of scalability initiatives without sacrificing security. Energy trading between platforms functions seamlessly when different blockchain networks are compatible. Possible research directions for enhancing interoperability include cross-chain communication techniques and standardization protocols.

Through the digitization and decentralization of the energy sector, blockchain technology is instrumental in expediting the decarbonization of the grid. Generating renewable energy can expedite the realization of a world powered exclusively by renewable energy by enabling the widespread distribution of local smart grids. When smart meters, high-speed communication, and blockchain integration are combined to streamline the renewable energy market, a technology-driven distributed renewable energy generation industry can be realized. To make it a reality, significant modifications to the laws and regulations governing power distribution are necessary.

7. Conclusions

Renewable energy possesses the capacity to address global energy demands while concurrently mitigating greenhouse gas emissions and enhancing air quality. Nevertheless, numerous obstacles and challenges have impeded the widespread implementation of renewable energy. These have been resolved with the advent of energy storage technologies, governmental subsidies and incentives, and technological advancements. Notwithstanding these resolutions, obstacles persist in the adoption of renewable energy that may be surmounted by employing blockchain technology. Blockchain technology offers a decentralized and transparent framework for monitoring and validating the production and utilization of renewable energy. This has the potential to enhance confidence and trust in the renewable energy market.

The incorporation of blockchain technology into renewable energy systems presents encouraging prospects for augmenting sustainability, transparency, and efficiency. The literature review elucidates a multitude of theoretical frameworks, research approaches, and discoveries within this field. Despite this, several voids remain, which suggest potential avenues for further investigation. An important area that requires further research is an exhaustive examination of the environmental ramifications associated with various consensus mechanisms in blockchain, specifically as they pertain to renewable energy. Furthermore, additional investigation is required to examine the capacity of blockchain solutions to accommodate the growing intricacy and magnitude of transactions within the realm of renewable energy trading scenarios over an extended period.

Exploration of novel blockchain-based consensus algorithms, such as the Hyper Delegation Proof of Randomness (HDPoR) algorithm, to enhance the infrastructure and performance of renewable energy transaction systems and overcome current limitations are among the prospects in this field. Furthermore, the progression of scientific inquiry regarding decentralized peer-to-peer energy marketplaces and governance frameworks will serve to enhance the progress of resilient and expandable resolutions. In the renewable energy sector, the realization of the complete potential of blockchain technology will require the cooperation of policymakers, academia, and industry to surmount technical, regulatory, and societal obstacles.

Although blockchain technology presents advantages such as decentralized energy trading and expanded access in the realm of renewable energy, some obstacles must be resolved, including user confidence, education, and the fair allocation of benefits. Collaboration between researchers, policymakers, and industry stakeholders is vital for effective integration. Inclusive societal and economic impacts are imperative, as they foster sustainable development and address the varied requirements of communities.

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