frontiers | Frontiers in Energy Research

TYPE Review
PUBLISHED 24 April 2024
DOI 10.3389/fenrg.2024.1393084

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OPEN ACCESS

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RECEIVED 28 February 2024
ACCEPTED 25 March 2024
PUBLISHED 24 April 2024

CITATION
Aoudia M, Alaraj MBM, Abu Waraga O, Mokhamed T, Abu Talib M, Bettayeb M, Nasir Q and Ghenai C (2024), Toward better blockchain-enabled energy trading between electric vehicles and smart grids in Internet of Things environments: a survey.
Front. Energy Res. 12:1393084.
doi: 10.3389/fenrg.2024.1393084

Toward better blockchain-enabled energy trading between electric vehicles and smart grids in Internet of Things environments: a survey

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With the rise of the 3Ds—decarbonization, decentralization, and digitalization—the number of electric vehicles is projected to increase, necessitating the implementation of modern technologies to avoid unnecessary energy wastage. Numerous studies have been developed proposing electric vehicle (EV) charging frameworks in networks empowered by renewable energy resources. In addition, more focus has recently been directed on incorporating blockchain technology to assure security and transparency in trading systems. However, fewer studies have delved into developing a practical implementation of their solution due to the complexity of the topic. Therefore, this paper thoroughly investigates integrating blockchain technology in electric vehicle charging systems, analyzing the existing practical implementation and their characteristics. It comprises 48 relevant studies between 2017 and 2023, covering the following main research areas: (i) renewable energy-based electric charging systems, (ii) blockchain frameworks used in energy trading, and (iii) performance metrics of simulated and implemented solutions. Results show that blockchain applications in EVs and energy trading systems are highly current, and researchers are actively exploring ways to improve their efficiency and effectiveness.

KEYWORDS

electric vehicles, blockchain, renewable energy charging, energy storage, energy trading

Abbreviations: RES, renewable energy source; EV, electric vehicle; CS, charging station; P2P, peer-to-peer; PV, photovoltaic; V2V, vehicle-to-vehicle; RET, renewable energy transaction; PoW, proof-of-work; PoS, proof-of-stake; PoC, proof-of-capacity; PoB, proof-of-burn; PoA, proof-of-authority; AI, artificial intelligence; V2V, vehicle-to-vehicle; SGs, smart grids; SLR, systematic literature review; IoT, Internet of Things; ID, identification; IDE, integrated development environment.

Highlights

- Increasing electric vehicles (EVs) and the 3Ds: With the rise of decarbonization, decentralization, and digitalization, the number of electric vehicles is projected to increase significantly, necessitating the implementation of modern technologies to avoid unnecessary energy wastage.
- Incorporating blockchain technology: Integrating blockchain technology in electric vehicle charging systems has gained attention as a way to ensure security and transparency in energy trading systems.
- Practical implementation challenges: Although numerous studies propose EV charging frameworks empowered by renewable energy resources and blockchain, fewer studies have focused on developing practical implementations due to the complexity of the topic.
- Research areas covered: The review study analyzed 48 relevant studies between 2017 and 2023, covering three main research areas: renewable energy-based electric charging systems, blockchain frameworks used in energy trading, and performance metrics of simulated and implemented solutions.
- Current state of blockchain applications: Results show that blockchain applications in EVs and energy trading systems are currently high, and researchers are actively exploring ways to improve their efficiency and effectiveness.
- Blockchain technology overview: The paper overviews blockchain technology, including its decentralized storage, different types of blockchain networks (public, permissioned, and private), and consensus protocols (such as proof-of-work and proof-of-stake).
- Smart contracts and smart grids: The role of smart contracts, computer programs executed in a blockchain platform, is discussed, along with the concept of smart grids and their use in efficient energy flow management.
- Challenges and solutions: The paper highlights challenges in the current electricity management systems, such as inefficient energy transfer and climate change, and discusses how integrating blockchain, smart contracts, and IoT technologies with smart grids can address these challenges.
- Analysis of existing surveys: The study reviews other surveys related to the field and analyzes their coverage of topics, such as blockchain, EVs, renewable energy generation, electricity charging, and energy storage. It identifies a gap in the literature and aims to provide a comprehensive analysis of blockchain applications in the energy management sector.
- Methodology: The review article follows a systematic literature review (SLR) methodology, including planning, conducting, and reporting phases. It outlines the research questions, search strategy, criteria for paper selection, quality assessment rules, data extraction method, and synthesis of the extracted data.
- Contribution and future directions: The article contributes to the field by exploring different electric management systems, analyzing various blockchain networks, evaluating system performance, highlighting limitations of existing systems, and identifying future research directions and challenges.

These highlights provide an overview of the key points covered in the review article on blockchain-enabled energy trading between electric vehicles and smart grids in IoT environments.

1 Introduction

The transition toward sustainable energy systems is characterized by three fundamental shifts, namely, decarbonization, decentralization, and digitalization, often referred to as the 3Ds. These shifts are increasingly relevant in the context of electric vehicles (EVs), which are projected to constitute 50% of the new vehicle market in the near future (Sexauer et al., 2011). This surge in EV adoption necessitates the integration of advanced technologies to ensure efficient energy utilization and support the overarching objectives of sustainable urban development. The advent of blockchain technology, alongside the Internet of Things (IoT) and related digital innovations, has emerged as a pivotal element in the evolution of smart city infrastructures. However, the current electricity management paradigms, plagued by inefficiencies and environmental concerns, demand a transformative approach to integrate renewable energy sources seamlessly with the existing grid systems (Tuballa and Abundo, 2016; Pavon et al., 2021; Si et al., 2021).

Blockchain, a decentralized ledger technology, was introduced in 2008 by Satoshi Nakamoto, revolutionizing data management with its immutable and transparent characteristics (Zamfirescu et al., 2019; Nakamoto, 2023). This technology, characterized by a sequential chain of data blocks linked through cryptographic hashes, guarantees the integrity and immutability of stored information (Yap et al., 2023). Each block encapsulates data elements like timestamps, transactions, and nonces, ensuring a robust audit trail, as depicted in Figure 1.

The diversity of blockchain networks, categorized into public, permissioned, and private domains, reflects the varying levels of access and participation. Public blockchains like Ethereum offer open access, whereas permissioned and private networks impose access restrictions, influencing network scale and operational dynamics (ethereum.org, 2023). The heart of these networks lies in their consensus protocols, which are mechanisms ensuring ledger consistency across all nodes. These protocols, including proof-of-work (PoW) and proof-of-stake (PoS), vary in attributes such as transaction speed, scalability, and security (Xie et al., 2018; Krishnamoorthi et al., 2023). The evolution from PoW to more efficient protocols like PoS reflects ongoing advancements to mitigate computational and energy inefficiencies (King and Nadal, 2012). Figure 2 illustrates the operational mechanism of the PoS protocol.

Smart contracts and automated executable codes further extend the utility of blockchains , enabling self-executing agreements based on predefined conditions (Szabo, 1996; Zheng et al., 2020). These contracts, once deployed on blockchain platforms like Ethereum and Hyperledger Fabric, facilitate transparent and secure transactions without intermediaries, ensuring trust and integrity in digital interactions (Wang et al., 2018; Amazon, 2023).

The concept of an electric grid encompasses the generation, transmission, distribution, and control of electricity. In this context, smart grids represent an advanced infrastructure paradigm, leveraging IoT and sophisticated algorithms to enhance energy efficiency and management (Fang et al., 2012; Siano, 2014). The integration of EVs and renewable energy sources (RESs) into smart grids introduces variability in power generation, necessitating innovative management strategies to maintain power quality and

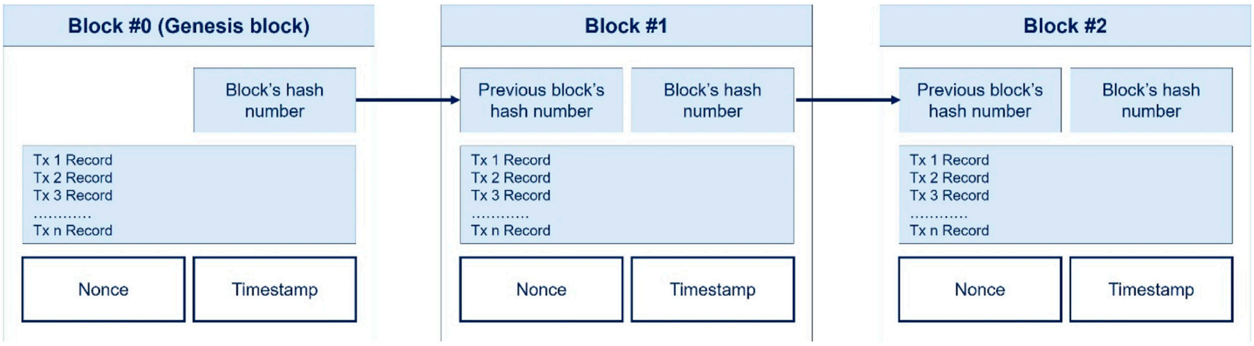

FIGURE 1
Blockchain structure.

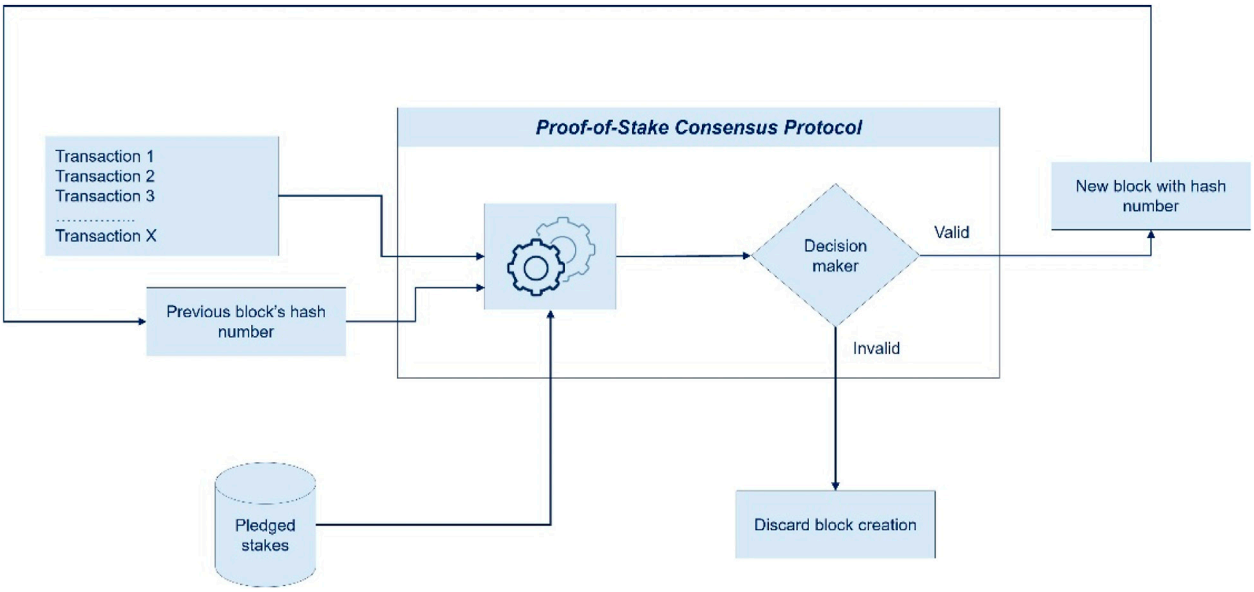

FIGURE 2
PoS consensus protocol mechanism.

system stability (Dharmakeerthi et al., 2011; Ahmadi et al., 2019; Galus et al., 2019). Effective scheduling of EV charging, supported by auction-based mechanisms, can optimize energy consumption and pricing dynamics, thereby mitigating energy loss and enhancing grid efficiency (Sarenche et al., 2021). Given the environmental concerns, fossil fuel depletion, and the ascent of multi-energy system structures, there is a growing emphasis on the integration of blockchain technology in smart grids (Zhang N. et al., 2022). Energy storage (ES) plays a pivotal role in enhancing power quality and reliability within these grids, particularly in managing the variability of renewable energy sources and ensuring their dispatchability (Zhong et al., 2020). The rise of smart grids, underscored by their reliability, efficiency, and sustainability, necessitates sophisticated control and management of diverse energy devices to balance supply and demand economically (Ding et al., 2018).

This review paper delves into the incorporation of blockchain technology within EV charging systems powered by renewable energy, spanning research from 2017 to 2023 and carefully examining 48 academic publications (Li and Hu, 2021; Yahaya et al., 2020; Li and Hu, 2020; Samuel et al., 2020; Samuel et al., 2022; Zhang Q. et al., 2022; Liang et al., 2022; Liu et al., 2022; Kumar et al., 2023; Wang et al., 2023; Chen et al., 2021; Hassan et al., 2022; Wen et al., 2022; Lasla et al., 2020; Khalid et al., 2020; Dorokhova et al., 2021; Cavalcante et al., 2023; Bouachir et al., 2022; Barnawi et al., 2021; Mhaisen et al., 2019; Javed et al., 2021; Florea, 2020; Javed et al., 2020; Akhter et al., 2022; Zhang S. et al., 2022; Zhao et al., 2022; Salmani et al., 2022; Li et al., 2020; Munsing et al., 2017; Zhang et al., 2018; Meena and Yang, 2019; Elliott et al., 2020; Wang and Zhang, 2022; Li et al., 2021; Baza et al., 2021; Zhou et al., 2019; Debe et al., 2021; Javed and Javaid, 2019; Luo et al., 2022; Khalid et al., 2021; Abishu et al., 2022; Liu et al., 2019; Seven et al., 2020). The exclusion of non-academic sources was deliberate, prioritizing scientific rigor. The analysis adhered to Kitchenham's systematic literature review methodology (Kitchenham and Charters, 2007).

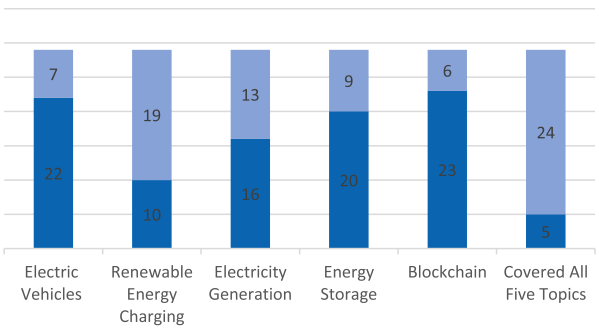

FIGURE 3
Number of papers covering each topic.

Subsequent sections will explore the related literature, methodology, main findings, forward-looking recommendations, and conclusions, thereby addressing the gaps identified in prior studies and outlining the direction for future research.

2 Literature review

The field of integrating blockchain technology with electric vehicle (EV) charging systems is expanding rapidly, making it necessary to comprehensively review the existing literature to identify current research trends, methodologies, and gaps. To this end, we utilized "Publish or Perish" software (Harzing, 2023) to amass a preliminary collection of 35 surveys related to blockchain, EVs, renewable energy generation, electricity charging, and energy storage. After a meticulous screening process, 29 surveys were deemed relevant for further analysis. Figure 3 illustrates the distribution of these surveys across the specified topics. The chart reveals that most studies focused on blockchain, EVs, and energy storage, while fewer surveys address electricity charging directly. Notably, a mere 17.24% of these surveys encompass all the topics, although concisely, signifying a research void in comprehensively addressing these interconnected fields.

After identifying the topics, the surveys were assessed qualitatively to evaluate their thoroughness in covering the subject matter, rated as low (L), medium (M), or high (H). Table 1 shows the level of detail each survey provides on five central themes, aiding in spotting research trends and gaps. This evaluation particularly underscored the lack of detailed research in the areas of electricity charging and energy storage. It was found that there is extensive research on blockchain and renewable energy generation, likely due to the increasing interest in integrating these fields with energy management systems. However, there is a discernible deficiency in detailed studies on energy storage systems, which are often assumed to integrate smoothly with the grid without requiring separate scrutiny.

In dissecting individual contributions, Adil et al. (2021) proposed integrating EV energy trading using the Stackelberg game theory, emphasizing the strategic interaction of rational actors in the market. However, their analysis underrepresented the potential of blockchains in enhancing grid systems. Bao et al. (2020) concentrated on the role of blockchains in monitoring and scheduling EV charging, recognizing the technology's security and privacy benefits. Yapa et al. (2021) envisioned Smart Grid 2.0, integrating diverse energy sources and real-time control through Internet connectivity, proposing a future grid model that leverages blockchain and artificial intelligence (AI) for energy trading. Baashar et al. (2021) highlighted AI's potential in predicting and optimizing EV charging schedules within blockchain-based systems, while Aggarwal et al. (2021) explored advanced concepts like vehicle-to-vehicle (V2V) charging and market mechanisms within blockchain-enabled smart grids.

This literature review also acknowledges other noteworthy surveys like those by Guo et al. (2022), who emphasized the use of blockchains in grid systems, and Zafar and Ben Slama (2022), who focused on integrating blockchains with Smart Grid 2.0. These works, despite their valuable insights, did not fully address the electric charging mechanisms, indicating a research opportunity. Our analysis extends beyond identifying topical coverage to evaluating the statistical and methodological rigor of the surveyed literature. Many studies lack detailed explanations of their statistical approaches and the reproducibility of their findings, an aspect critical for advancing research in this domain.

Institutional research trends indeed show that universities and research centers with strong engineering and technology programs, such as MIT and Stanford, are leading in blockchain and renewable energy research (MIT Energy Initiative, 2024; Stanford Center for Blockchain Research, 2024). The MIT Energy Initiative, for instance, is developing sustainable, low-carbon solutions to meet the world's energy demands (MIT Energy Initiative, 2024). Similarly, the Stanford Center for Blockchain Research is focusing on cryptocurrencies and blockchain technologies (Stanford Center

TABLE 1 Coverage of the top five surveys.

Author	Year	Blockchain	Electric vehicle	Renewable energy generation	Electricity charging	Energy storage
Adil et al. (2021)	2021	L	M	M	H	M
Bao et al. (2020)	2020	H	H	L	M	L
Yapa et al. (2021)	2021	H	L	H	H	M
Baashar et al. (2021)	2021	H	M	H	L	L
Aggarwal et al. (2021)	2021	H	M	H	L	M

TABLE 2 Research questions used for evaluation.

No.	Research question	Description
RQ1	Is the infrastructure of the simulation/implementation provided?	Determines the platforms, tools, software, parameters used, renewable energy sources examined, and the grid connection of utility power and EVs
RQ2	What are blockchain applications?	Identifies the chosen blockchain platform/framework, parameters saved in the blockchain, and the types of data stored, including transactions, signatures, and metadata
RQ3	Was the simulation/implementation evaluated?	Assesses the technical feasibility, reliability, achievement of goals and objectives, and long-term impact on the environment and society, focusing on energy conservation and efficiency
RQ4	What are the challenges addressed/faced?	Examines the technical, financial, and other challenges encountered during the study

TABLE 3 Search terms used.

Search string
'Electric vehicles' **OR** 'EV/PV' **AND** 'blockchain'
'Renewable energy charging' **AND** 'Electric vehicles' **AND** 'blockchain'
'Electricity generation' **AND** 'Electric vehicles' **AND** 'blockchain'
'Energy storage' **AND** 'Electric vehicles' **AND** 'blockchain'
'Electric vehicles' **AND** ('Renewable energy' **OR** 'Electricity generation') **AND** 'Energy storage' **AND** 'Blockchain'

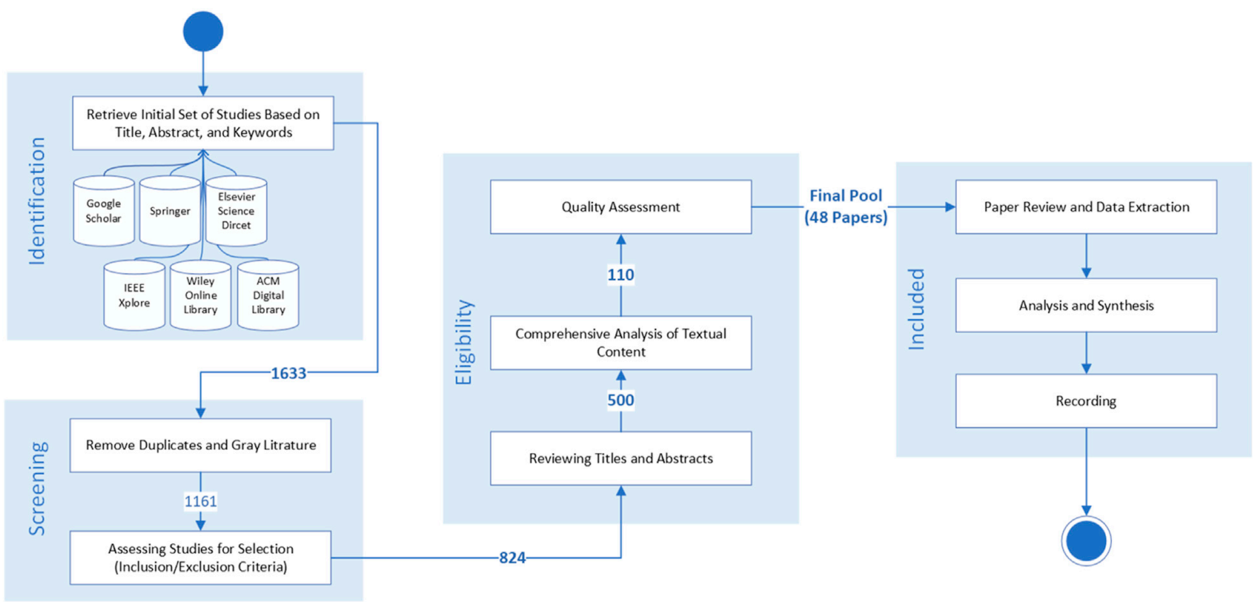

FIGURE 4
Systematic literature review process according to Kitchenham and Charters (2007).

for Blockchain Research, 2024). The innovative use of blockchain to enhance grid management and EV integration is a strength of these approaches (Wang et al., 2020). For example, the Mobility Open Blockchain Initiative (MOBI) standard for grid integration of electric vehicles incorporates blockchain technology into a decentralized charging system.

In conclusion, our literature review fills the existing research gap by providing an examination of blockchain applications in smart energy and electricity management (Silva et al., 2019), highlighting system performance, identifying limitations, and providing recommendations for future research. Our contributions aim to enhance the understanding of electric management systems,

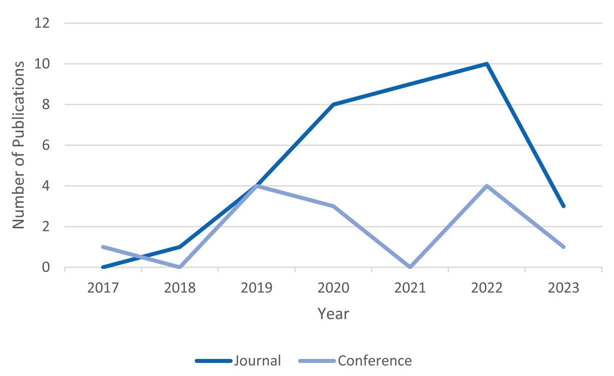

FIGURE 5
Publication types along with their respective years of publication.

evaluate blockchain networks for energy applications, and propose a comprehensive, methodologically sound research framework.

3 Methodology

The study described in this paper is based on the systematic literature review (SLR) methodology developed by Kitchenham and Charters (2007). The methodology consists of three phases: planning, conducting, and reporting. The planning phase is further divided into six stages. Initially, research questions were formulated based on the objectives of the review. A strategy was then devised to locate relevant research papers, which involved identifying appropriate search terms and criteria for paper selection. Guidelines were established to determine which studies should be included or excluded. Additionally, quality assessment rules were designed to filter the research papers. A method was outlined for extracting data from the selected studies that met the predetermined criteria. Finally, the extracted data from the chosen studies were synthesized to address the research questions. The subsequent sections of the paper will present an overview of the review protocol used in this study.

3.1 Research questions

Our objective is to examine the potential enhancements in communication, energy trading, and overall system efficiency through the integration of blockchain technology, smart contracts, and the Internet of Things (IoT) within the interaction between EVs and smart grids (SGs). This investigation is driven by the ambition to achieve the strategic imperatives of decentralization, decarbonization, and digitalization, collectively referred to as the 3Ds. To systematically address this objective, we have delineated a structured set of research questions. These questions are methodically organized in Table 2, outlining each question's focus and its corresponding investigative parameters.

3.2 Search strategy

This section presents the systematic approach adopted for the search process in this review.

3.2.1 Search items

The formulation of search terms was methodically approached, as described in this study:

- Keywords were extracted from the research questions to derive the primary search terms.
- Supplementary terms, including abbreviations and synonyms, were incorporated to broaden the search scope.

Advanced search techniques, such as Boolean operators ("AND" and "OR") and phrase searching with quotation marks, were used to refine and focus the search results. Table 3 summarizes the search terms used to collate relevant literature records, utilizing varied terms to augment the retrieval of relevant publications.

3.2.2 Literature resources

The systematic literature review was conducted by sourcing primary studies from six esteemed digital libraries, which are as follows:

1. Google Scholar
2. Springer
3. Elsevier ScienceDirect
4. ACM Digital Library
5. IEEE Xplore
6. Wiley Online Library

To facilitate a comprehensive and efficient search, pre-established search terms were utilized to query both journal and

TABLE 4 Inclusion and exclusion criteria for the selected studies.

Inclusion criteria	Exclusion criteria
Papers should be published after 2016 to discuss the integration of blockchain technology in energy trading and the electric vehicle sector	These are papers that do not discuss the integration of blockchain technology in energy trading and the electric vehicle sector
Papers that present case studies or experiments	Papers that are not written in English or that are not published in reputable journals or conferences
Papers that analyze the challenges, limitations, potential impact, and related issues regarding blockchain usage	Papers that focus exclusively on the technical aspects of blockchain technology without discussing its practical applications in the electric vehicle sector
Papers that provide a clear definition of blockchain technology and its underlying principles	

TABLE 5 Quality assessment rules.

No.	Description
QAR1	Are the study objectives clearly recognized?
QAR2	Is the system background explained?
QAR3	Is the EV charging system infrastructure defined?
QAR4	Is the blockchain clearly defined?
QAR5	Are the strengths of the proposed methods well explained?
QAR6	Are the limitations of the proposed methods well-explained?
QAR7	Are the methods well-designed and justifiable?
QAR8	Is the proposed methodology tested/experimented?
QAR9	Are evaluation results reported?
QAR10	Overall, does the study enrich the academic community or industry?

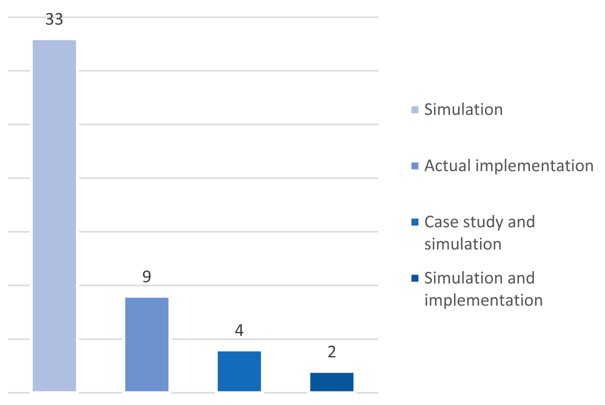

FIGURE 6
Types of conducted experiments.

conference papers across these electronic databases. The search terms were designed to align with the syntactic requirements of each database's search engine, ensuring the retrieval of relevant academic resources.

3.2.3 Search process

To effectively perform a systematic literature review (SLR), it is essential to conduct an exhaustive search of all relevant sources. Therefore, we established a two-phase search strategy. It should be emphasized that only the papers fulfilling the criteria discussed in the subsequent section will be acknowledged as relevant.

- **Phase 1:** identifying a collection of papers through the search of six electronic databases and compiling the papers retrieved.
- **Phase 2:** broadening this collection by reviewing the reference lists of the identified papers and incorporating any additional relevant papers discovered.

Mendeley Reference Manager software, developed by Elsevier, was utilized to organize the research papers. Through our search strategy, we identified 48 relevant papers, as summarized in Figure 4. The next section will provide a detailed explanation of the criteria for inclusion and exclusion.

3.3 Study selection

Utilizing specific search criteria, we refined an initial collection of 824 publications down to 48 that were relevant to our study, covering the period from 2017 to 2023. This refinement was achieved through a series of screening and selection steps. Figure 5 displays the yearly distribution of the selected papers. The methodology used for the selection process included the following steps:

1. Elimination of duplicate articles.
2. Application of predefined inclusion and exclusion criteria.
3. Verification that the selected articles aligned with our research objectives and maintained high-quality standards.

The primary criteria for including and excluding studies are documented in Table 4.

3.4 Quality assessment rules

The research utilized a set of quality assessment rules (QARs) to evaluate the relevance and quality of articles collected based on the study's research objectives. A total of 10 QARs were formulated, with each criterion contributing a maximum of one point to an article's total score, with a maximum possible score of 10 points. , and The specific QARs are outlined in Table 5, and the scoring system is as follows:

1. Responded completely: 1 point
2. Above average: 0.75 points
3. Average: 0.5 points
4. Below average: 0.25 points
5. Not answered: 0 points

3.5 Data extraction strategy

In this phase, the selected articles were used to collect information relevant to the study's research questions. Key information, such as the article's ID, title, publication year, type, publisher, and responses to the research questions (RQ1, RQ2, RQ3, and RQ4), was extracted from each article. It is important to note that not all articles contained answers to every research question. The data gathered from each article were systematically classified, arranged, and stored in a spreadsheet for subsequent analysis.

3.6 Synthesis of extracted data

To summarize the data collected from selected studies, we used various methods to compile the findings for each research question. Specifically, we adopted narrative synthesis as a method to organize

TABLE 6 Research studies and the type of experiments conducted.

Type of experiment conducted	Paper ID	Total number of papers
Simulation	[R1–3, R5, R6, R9, R11, R13–20, R23–30, R33, R35, R36, R37, R38, R39, and R45–48]	33
Actual implementation	[R4, R10, R12, R21, R22, R34, R40, R41, and R42]	9
Simulation and implementation	[R7 and R8]	2
Case study and simulation	[R31, R32, R43, and R44]	4

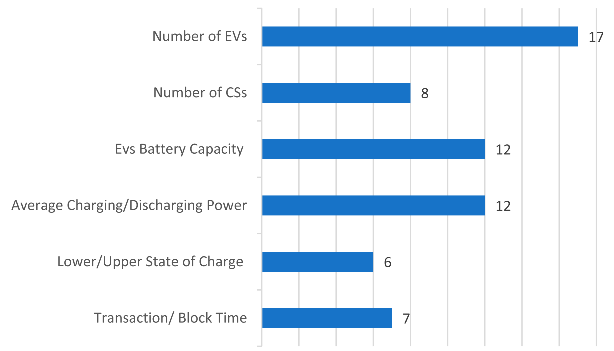

FIGURE 7
Frequency of parameters in smart grids and EV experiments.

and tackle research queries. This approach involves the orderly arrangement and display of research results, using diagrams and tables to visually depict the findings.

4 Results and discussions

This section presents the outcomes of the systematic literature review conducted. Initially, an overview of the selected studies is provided. Subsequently, the findings for each research question are discussed individually in distinct subsections. The discussion encompasses interpretations of the review results concerning the research questions, alongside considering related dimensions intimately connected with the research questions. To substantiate the credibility of our analysis, we incorporate corroborative evidence from pertinent works in the field. Supplementary Appendix SA includes a detailed compilation of all the papers reviewed, complete with their identification numbers.

4.1 Overview of the selected studies

The search protocol used in this review included studies post-2016, underscoring that the selected papers are contemporary and reflecting the burgeoning interest in the application of blockchain technology in electric vehicles and energy trading. As illustrated in Figure 5, a significant proportion of the selected studies (29.2%) were published in 2022, with a smaller fraction (8.3%) emerging in 2023. This is succeeded by 22.9% of the papers published in 2020 and 18.7% in 2021. These figures manifest a robust and escalating engagement in this domain, highlighting the growing acknowledgment of the potential benefits of blockchain. The upward trajectory in publications since 2017 also indicates an active investigation into diverse methodologies to harness blockchain technology for improving electric vehicles and energy trading systems' efficiency and effectiveness. The year-wise distribution of selected papers may be attributed to factors like funding availability, academic and industry interest, and technological progress in the sector.

The "publication type" of a research paper significantly influences its prominence and impact within a specific scholarly domain. It is demonstrated that most of the selected studies (73%) were disseminated through academic journals, with the remaining 27% presented at conferences and included in their proceedings, indicating a varied range of dissemination mediums.

4.2 Experimentation infrastructure and energy management systems

Our systematic literature review revealed several key findings in exploring the integration of blockchain technology with EVs and energy management systems. The examination focused on experimentation methods, smart grid configurations, blockchain technology applications, and the outcomes of these implementations.

TABLE 7 Papers and the RES type used.

Type of RES adopted	Paper ID	Total number of papers
Solar energy	[R1, R6–8, R12, R13, R19, R22, R31, R35, R36, R40, R43, and R48]	14
Wind turbines	[R8, R13, and R36]	3
Waterpower	[R13]	1
Not mentioned explicitly	[R2–5, R9–11, R14–18, R20, R21, R23–R30, R32–34, R37–39, R41, R42, and R44–47]	34

TABLE 8 Proposed schemes and blockchain applications.

ID	Proposed scheme	Blockchain application
R3	Decentralized scheme using consortium blockchain for EV and power grid bidirectional trading	Energy trading
R4	Privacy-focused charging scheme for EVs utilizing blockchain	Energy trading
R5	Smart contract-based control approach for secure operations of battery energy storage systems (BESSs)	Energy trading
R6	Peer-to-peer energy market using blockchain and smart contracts for fair payment distribution and optimization	Energy trading and data storage
R8	Energy trading architecture for EVs in smart cities using blockchain and existing utility infrastructure	Energy trading and charging prioritization
R9	Robust and secure energy trading model based on blockchain, with contract theory and a reputation system	Energy trading
R10	Secure energy system for EVs in sustainable cities using private and public blockchains is needed	Load balancing
R13	Blockchain-based platform for P2P energy trading and sharing with federated learning	Energy trading and trust and privacy
R14	Distributed multi-party electric energy transaction mechanism based on blockchain	Energy trading and transaction verification
R15	Vehicle-to-vehicle (V2V) electricity trading strategy based on consortium blockchain	Energy trading
R16	Decentralized trading architecture using consortium blockchain for EV and smart grid trading	Energy trading
R17	Blockchain network and smart contracts for optimized P2P electricity transaction pricing	Energy trading
R18	Two energy trading schemes for EV integration into the smart grid using blockchain	Energy trading
R19	Decentralized system with privacy, security, prioritization, and blockchain-based EV incentives	Energy trading
R21	Energy trading system using Ethereum smart contracts for secure and transparent exchange	Energy trading
R22	Energy management system for solar-powered EV charging stations using blockchain	Energy trading and data recording
R23	Privacy-preserving scheme for EV charging using consortium blockchain	Enhancing guiding capability
R24	Blockchain-based approach preserving the EV location and preventing attacks	Energy trading
R25	Mobile-vehicle-to-vehicle (M2V) charging strategy for EVs using blockchain	Energy trading
R26	Energy trading management system for EVs based on blockchain using smart contracts	Energy trading
R27	Security and efficiency for real-time energy trading between vehicles and grid in smart cities using consortium blockchain	Energy trading
R28	Energy trading system for EVs and charging stations using blockchain and energy broker	Energy trading and privacy preservation
R30	Proof-of-benefit consensus mechanism for managing EV charging loads	Energy trading
R31	Bidding model leveraging blockchain for coordinated EV and photovoltaic development	Energy trading and solving privacy issues
R32	Blockchain-based system for improved data security and privacy	Energy trading and data recording
R33	Blockchain-based solution for EV range and battery management using IOTA tangle	Energy trading
R34	Peer-to-peer energy trading scheme for virtual power plants using smart contracts	Energy trading
R35	Blockchain-based solution for hybrid P2P energy trading markets with smart contracts	Energy trading
R37	System enabling surplus electricity sale and charging bill payment using blockchain	Energy trading
R38	Smart contract-based inference engine for EV data retrieval, decision-making, and activation	Energy trading and data storage
R39	Peer-to-peer charging mechanism using blockchain for privacy, security, and trust	Data storage
R40	Charging management framework for EVs based on the Ethereum blockchain	Energy trading
R41	System was implemented for energy trading on Hyperledger Fabric	Energy trading
R43	Blockchain-based framework for energy trading among institutions and EV owners	Energy trading and transaction verification
R44	Blockchain-based solution for transactive energy in distribution network operations	Energy trading and transactions
R45	Smart contract-based solution for energy sharing with credit point integration	Energy trading and transaction verification
R46	V2GNet system integrates blockchain for secure and efficient energy trading	Data Storage and transaction verification

(Continued on following page)

TABLE 8 (*Continued*) Proposed schemes and blockchain applications.

ID	Proposed scheme	Blockchain application
R47	Blockchain-based anonymous identity authentication scheme for secure mutual authentication	Data storage and transaction verification
R48	Smart contracts and consortium blockchain for an efficient and reliable trading process	Charging and discharging scheduling

TABLE 9 Blockchain frameworks used.

ID	Blockchain framework
[R3, R4, R16, R17, R22, R36–38, R41, and R48]	Hyperledger Fabric
[R6, R8, R13, R18, R21, R24, R30–32, R34, R35, R39, R40, and R42–44]	Ethereum
[R9, R19, R20, R23, R25, R27–29, and R33]	Consortium blockchain
[R5]	Private blockchain
[R1 and R26]	Consensus mechanism
[R2, R7, R10–12, R14, R15, and R45–47]	Not mentioned explicitly

4.2.1 Experimental approaches in blockchain applications

In this systematic literature review, we examined 48 research papers that passed the selection criteria, all of which conducted experiments to validate their proposed systems. These experiments are broadly classified into four categories: simulation, actual implementation, a combination of simulation and implementation, and case studies with simulation. According to Figure 6, a percentage of 68.75 of the studies utilized simulation methods. Meanwhile, actual implementations, case studies, and combined simulation and implementation accounted for only 1%, 8%, and 4%, respectively, as indicated in Figure 6. This preference for simulation is attributed to its practicality in testing hypotheses without the necessity of physical prototypes, ensuring both cost-effectiveness and precision in results. Table 6 details the categorization of experiments across the reviewed papers. Most of the research utilized tools like Remix IDE, Ganache, and the Solidity programming language to construct and evaluate the blockchain network's performance, which was integral to their experiments. Additionally, MATLAB was used extensively in Li and Hu (2020); Samuel et al. (2020); Yahaya et al. (2020); Li and Hu (2021); Zhang Q. et al. (2022); Liang et al. (2022); Liu et al. (2022); Samuel et al. (2022); Kumar et al. (2023) as a platform for simulating and analyzing the proposed grid systems' capabilities and constraints.

To effectively develop frameworks that address decentralization, decarbonization, and digitalization (the 3Ds), it is crucial to analyze the parameters selected for experimentation within the existing literature. This analysis revealed diversity in the experimental parameters across the studies. Only a minority of studies (three studies) did not specify their parameters clearly. A systematic review of the parameters shows that certain parameters are recurrent and influential in the research field. Key parameters identified include the number of electric vehicles (EVs), the number of charging stations, battery capacities of EVs, average charging/discharging power, and lower and upper limits of the state of charge (SoC).

Figure 7 illustrates the frequency of these experimental parameters, helping in highlighting the most tested factors in smart grid and electric vehicle systems. The number of EVs, EV battery capacity, and average charging and discharging power were identified as the most repeated parameters, with counts of 17, 12, and 12, reflecting their importance in evaluating the system's performance. Additionally, the number of nodes representing EVs and charging stations influences the experimental setup's complexity and variability. Transaction and block times provide insights into the network's operational speed and efficiency. Other factors, such as SoC boundaries and battery capacity, play a significant role in the practical implementation at the individual system level.

4.2.2 Analyzing smart grid configurations

The section on smart grid configurations delves into the aspects of electricity generation and management within smart grid models. To accurately understand the utilized smart grid model, it is essential to identify critical specifications related to the setup, including the type of grid, RESs used, and the supported vehicles within the system. Incorporating RESs into smart grids presents opportunities to increase the utilization of green energy and enhance overall system efficiency. For instance, the adoption of solar energy, which is comparatively simpler to implement than wind turbines, can facilitate more flexible energy flow. Photovoltaic (PV) panels, for instance, can be installed on rooftops or vehicles, minimizing energy losses and incentivizing consumers to engage as prosumers, potentially benefiting from surplus energy sales. Table 7 provides an overview of different RES types and the number of research papers that studied each type. The total numbers may not align precisely due to some papers investigating combinations of renewable energy sources in a single system. Notably, PV panels exhibit clear advantages over wind turbines, as evidenced by the data presented. Papers that did not explicitly specify the type of RESs are categorized as "not mentioned explicitly," indicating a research gap regarding the integration of renewable sources that merits attention. The geographic location significantly influences the choice of RESs, with areas closer to the equator favoring PV panels over wind turbines due to their efficiency under specific climatic conditions. Khalid et al. (2020); Lasla et al. (2020); Chen et al. (2021); Dorokhova et al. (2021); Hassan et al. (2022); Wen et al. (2022);

TABLE 10 Evaluation results for the selected papers.

ID	Evaluation results
R1	The system is superior to existing solutions based on performance metrics
R2	Simulation results show increased income, balance charging costs, P2P energy transactions, and grid ancillary services
R3	Simulation results show that the proposed model smooths load fluctuations and improves the security and privacy of power trading
R4	Demonstrates advantages through theoretical analysis and experimental results
R5	The approach utilizes distributed network nodes and consensus mechanisms as smart contracts, resulting in robustness against cyber-attacks
R6	The first work is to examine the use of blockchain technology for distributed optimization and control in energy markets, addressing trust, security, and transparency
R7	The proposed SMERCOIN system increases solar energy usage through simulations and experiments
R8	The proposed smart contract-based trading platform supports energy trading transactions and charging requests from EVs in crowded cities
R9	The proposed model was evaluated using various metrics, including social welfare and the utility of the local aggregator, with privacy and security analysis
R10	The proposed system improves efficiency and security in terms of energy price, operating cost, and privacy protection
R13	Smart contracts predict energy demand and production, resulting in decreased energy costs for consumers and decreased load on utility grids
R19	The system's effectiveness is verified through simulation
R24	Simulation results show that increasing privacy levels reduces the risk of revealing sensitive information
R25	Simulation results show that the proposed system is more efficient than conventional techniques in minimizing EVs' charging cost, time, and distance
R26	Simulation results show that the proposed system improves social welfare and cost performance
R27	The proposed system surpasses existing solutions in offering a secure and efficient energy trading platform
R28	The proposed model is secure and efficient, reducing risk factors by almost 25%–30% and data redundancy by almost 40%–50%
R29	The proposed scheme reduces buyers' costs by 21.1% and increases sellers' utility by 18%, with improvements in transaction processing delay and throughput
R30	The ONPoB algorithm reduces the power fluctuation level (PFL) compared to popular scheduling algorithms
R31	The suggested model offers an optimized scheduling plan, reducing the carbon emissions of active distribution networks
R34	The suggested scheme tackles the financial elements of P2P trading, diminishing energy expenses while enhancing security and transparency
R35	The proposed model demonstrates enhanced efficiency in reducing the cost and peak-to-average ratio of electricity
R37	The proposed system decreases human involvement, enhances trust, transparency, and privacy among EV participants, and assists policymakers in smart cities
R39	Simulation results demonstrate efficiency in minimizing charging costs, time, and distance
R40	Results illustrate the viability of the proposed blockchain framework for EV charging and smart grid projects
R42	The suggested system mitigates the demand for EV charging stations and offers an affordable solution for sharing home charging stations
R43	Implementing blockchain in energy trading and EVs results in substantial CO_2 emission reductions, and customers benefit from a 25% lower price
R45	Smart contracts and blockchain technology in energy trading improve performance, increase the energy transaction volume, and revolutionize energy markets
R46	Implementing the RET algorithm ensures a 64% stable energy demand fill rate and reduces energy loss by 30%
R47	The proposed approach shows a 30% increase in the peak-to-valley ratio, enhancing stability and reducing energy supply variations
R48	The BQL-ET system demonstrates lower market trading price, 16%–40% better load consumption, optimized energy consumption, and improved energy trading performance

Cavalcante et al. (2023); Kumar et al. (2023); and Wang et al. (2023) predominantly utilized solar panels as their primary RES, highlighting the prevalent preference for solar energy in smart grid configurations. Conversely, fewer papers, including Lasla et al. (2020), Bouachir et al. (2022), and Wang et al. (2023), explored wind turbines, noting their requirement for substantial initial investment and suitability for more isolated areas to minimize disturbances.

The configuration of the grid's connection, termed grid connection, defines the grid's topology. A grid-tied connection indicates a system interconnected with aggregators, allowing for the participation of prosumers and decentralized energy generation

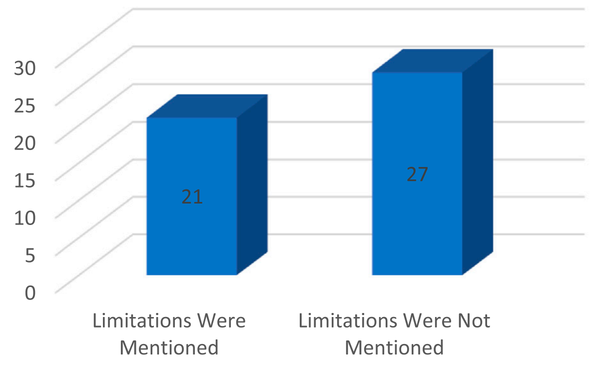

FIGURE 8
Comparative quantification of papers addressing limitations within their studies.

from locations such as homes and buildings. On the other hand, an off-grid system lacks flexible energy transfer but incorporates energy storage mechanisms. Among the analyzed papers, 75% of the 48 studies utilized a grid-tied connection. This high prevalence suggests the efficacy and recommendation of using grid-tied connections within smart grid configurations for enhanced efficiency and adaptability.

4.3 Blockchain technology in electric vehicles and energy trading

4.3.1 Implementation and deployment trends

The examination revealed that a limited subset of publications (9 out of 48) presented implemented solutions, as depicted in Figure 6. Regarding the types of conducted experiments, notably, most publications concentrated on simulating potential blockchain-based solutions rather than actual implementations. The solutions that were implemented and deployed were identified mainly in recent years, specifically in 2018, 2020, 2022, and 2023. This trend reflects an increasing interest in applying blockchain technology in electric vehicles and energy trading, indicating a promising future for integration into these domains.

4.3.2 Advantages of blockchain in energy systems

Every study underscored the advantages of security and privacy features in blockchain-based energy systems, emphasizing the potential benefits of integrating blockchain technology in the energy sector (Sekaran et al., 2023). Various blockchain frameworks were explored for developing the proposed solutions, considering specific requirements, such as energy data, transaction data, user data, EV data, CS data, location data, payment data, contract data, security and immutability information, and other relevant parameters. In Table 8, various proposed schemes and blockchain applications are outlined, demonstrating the diverse applications of blockchain technology in energy trading and related domains. Similarly, Table 9 presents the blockchain frameworks utilized in these schemes, offering insights into the technological infrastructure supporting blockchain implementations.

4.4 Evaluation of experimentation outcomes

In this section, we conduct a comprehensive assessment of the results obtained from the experiments carried out in the selected primary research papers. Our evaluation includes a detailed analysis of the methodologies used, the accomplishments achieved, and the effectiveness of various approaches and techniques used. We meticulously examined each primary research paper and documented the evaluation results, which are synthesized into a structured format and presented in Table 10. These evaluation outcomes offer a nuanced understanding of the effectiveness and contributions of the researched papers. The findings underscore the diverse range of accomplishments, methodologies, and advantages stemming from the adoption of blockchain technology in electric vehicles, energy trading, and smart grid setups. These insights make a significant contribution to the ongoing discussions and advancements in the field, paving the way for further exploration and innovation.

4.5 Limitations to the proposed systems

This section underscores the importance of integrating blockchain technology into the trading of RESs. However, despite

TABLE 11 Limitations addressed in the literature review.

Limitation	Papers
System scalability issues	[R1, R5, R8, R20, R25, R28, R33, R39, R40, R42, and R43]
Blockchain network **limitations (e.g., no** support **for smart contracts or specific** transactions)	[R5, R32, and R44]
Centralization concerns and lack of decentralization	[R33]
Speed **disparities** between system layers	[R6, R16, and R38]
Challenges in predicting users' behavior	[R7]
Issues related to trust, privacy, and security	[R10, R23, R32, and R39]
Static **pricing mechanisms**	[R24]
Increased computational expenses	[R20, R28, and R40]

considerable research in this field, existing solutions face numerous challenges and limitations, such as performance, feasibility, and mass usage. Analyzing these challenges enables researchers to develop enhanced solutions. Based on the papers reviewed, the challenges faced can be categorized into two main groups: those related to the specifications of tools and technologies implemented (technology-dependent) and those related to environmental applications and individual cases (technology-independent). Unfortunately, many authors do not explicitly state the limitations of their studies and systems, leading to fewer challenges mentioned in the literature. Approximately 56.25% of the papers did not explicitly mention the challenges for the system they developed in their study, as depicted in Figure 8. Limitations addressed by the remaining studies are summarized in Table 11.

The most prevalent limitation observed was related to system scalability issues (Lasla et al., 2020; Dorokhova et al., 2021; Mhaisen et al., 2019; Florea, 2020; Javed et al., 2020; Barnawi et al., 2021; Javed et al., 2021; Akhter et al., 2022). Many papers noted that implementing systems on a blockchain network with a proof-of-work (PoW) consensus protocol requires substantial computational resources as the network size increases. Several papers also highlighted security concerns despite blockchain adoption (Samuel et al., 2022; Zhang S. et al., 2022; Zhao et al., 2022; Javed et al., 2020), often due to single points of failure in data management or reliance on centralized third parties. Ensuring a fully secure system remains challenging. Additionally, some papers mentioned the need for dynamic pricing mechanisms to replace static ones, particularly with the integration of RES and prosumer involvement (Samuel et al., 2020). Avoiding blockchain networks that lack smart contract support is crucial for ensuring the high functionality and reliability of frameworks (Florea, 2020).

To address these limitations effectively, certain conditions regarding blockchain and technologies must be followed. First, avoiding slow consensus protocols like PoW for large networks is essential. Second, minimizing centralized points and ensuring their security are crucial to prevent attacks and manipulation. Third, ensuring similar operating speeds across system layers enhances heterogeneous element interactions. Lastly, using machine learning models trained on charging behavior and related parameters can predict future charging loads and dynamically adjust energy prices for improved efficiency and reliability.

5 Recommendations and remarks

This study examines the utilization of blockchain technology in electric vehicle (EV) charging systems, focusing on its integration with renewable energy sources. After reviewing 48 academic papers, research directions or recommendations for future research have been identified to better understand and enhance this integration, with the goal of advancing effective and sustainable energy solutions. Key recommendations include the following: a) Future studies should include more extensive explanations of the blockchain architecture and its interaction with EV charging stations. This includes going over the technical requirements, operational procedures, and the role of blockchain in improving energy transaction security and efficiency. Diagrammatic representations and step-by-step explanations will help comprehend the complexity of these systems. b) More comprehensive statistical analysis is needed to validate the findings and ensure reproducibility. Future research should include detailed statistical methods, including data sampling, hypothesis testing, and confidence interval calculations, to substantiate the claims made. Additionally, examining the repetition of key parameters across studies will highlight the commonalities and variances in research focus, thus guiding more standardized and systematic investigations. c) Studies should focus more on how blockchain technology can enhance the integration of renewable energy sources within EV charging systems. This includes analyzing the impact of renewable energy on the efficiency and reliability of these systems, exploring innovative ways to manage the variability of renewable energy sources, and assessing long-term sustainability impacts. d) Explore how blockchain technology may be integrated with the latest technologies like artificial intelligence (AI) and machine learning (ML) in smart grids and EV charging systems. Investigating ways to use these technologies to improve real-time decision-making, forecast charging demands, and optimize energy distribution is required. e) A deep economic and market study of blockchain-enabled EV charging stations has to be a part of future research. This would involve market trends, cost-benefit analyses, and the economic feasibility of these systems under different market conditions and regulatory frameworks. Finally, f) evaluating the long-term impacts of integrating blockchain in EV charging systems is crucial, particularly concerning environmental sustainability, economic stability, and social equity. Research should focus on developing metrics and models to assess the long-term feasibility, sustainability impacts, and potential for scalable deployment of these systems.

6 Conclusion and future work

In summary, our literature review on the utilization of blockchain technology in electric vehicles and energy trading highlights the increasing advancements and interest within this domain. Our analysis of the 48 publications revealed that only a limited number of them presented tangible implementations, while the majority focused on simulations. However, it is noteworthy that the implemented solutions identified were published recently, indicating a growing trend and a promising future for the integration of blockchain technology in this field. The reviewed studies underscore the significance of considering privacy and security factors in blockchain-based energy systems and emphasize the potential benefits of incorporating blockchain technology in the energy sector. Future work could involve expanding the review's scope to encompass other related areas, conducting more comprehensive analyses of the implemented solutions, and exploring additional applications of blockchain technology in electric vehicles and the energy trading sector.

Author contributions

MeA: conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing–original draft, and writing–review and editing. MuA: conceptualization, data curation, formal analysis, investigation, methodology, software, visualization, writing–original draft, and writing–review and editing. OA: conceptualization, investigation, supervision, validation, visualization, writing–review and editing, and methodology. TM: writing–review and editing, conceptualization, investigation, methodology, supervision, validation, visualization, and formal analysis. MA: conceptualization, investigation, methodology, project administration, resources, supervision, validation, and writing–review and editing. MB: conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, and writing–review and editing. QN: conceptualization, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, and writing–review and editing. CG: project administration, supervision, validation, visualization, writing–review and editing, and resources.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. University of Sharjah.

Acknowledgments

The authors would like to thank the University of Sharjah and the OpenUAE Research and Development Group for funding this research study. They are also grateful to their research assistants, who helped collect, summarize, and analyze the research papers used in this SLR study.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2024.1393084/full#supplementary-material

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