Heliyon 10 (2024) e29600

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Blockchain technology in the renewable energy sector: A co-word analysis of academic discourse

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ARTICLE INFO

Keywords:
Blockchain technology
Electric vehicle
Renewable energy
Smart grid
Urban energy systems

ABSTRACT

The transformative potential of blockchain technology in the renewable energy sector is increasingly gaining recognition for its capacity to enhance energy efficiency, enable decentralized trading, and ensure transaction transparency. However, despite its growing importance, there exists a significant knowledge gap in the holistic understanding of its integration and impact within this sector. Addressing this gap, the current study employs a pioneering approach, marking it as the first comprehensive bibliometric analysis in this field. We have systematically examined 390 journal articles from the Web of Science database, covering the period from 2017 through the end of February 2024, to map the current landscape and thematic trajectories of blockchain technology in renewable energy. The findings highlight several critical thematic areas, including blockchain's integration with smart grids, its role in electric vehicle integration, and its application in sustainable urban energy systems. These themes not only illustrate the diverse applications of blockchain but also its substantial potential to revolutionize energy systems. This study not only fills a crucial gap in existing literature but also sets a precedent for future interdisciplinary research in this domain, bridging theoretical insights with practical applications to fully harness the potential of blockchain in the renewable energy sector.

1. Introduction

The renewable energy sector plays a crucial role in addressing contemporary global challenges [1–5]. As the world confronts climate change, environmental degradation, and the urgent need for sustainable development [6,7], renewable energy sources such as solar, wind, hydro, geothermal, and biomass offer sustainable solutions. While these sources are replenished naturally on a human timescale, they stand in stark contrast to finite fossil fuels, emitting little to no greenhouse gases and pollutants [8–11]. Statistics reflect the sector's growing significance. According to the International Energy Agency, clean energy investment has surged by 40 % since 2020, highlighting a robust commitment to reducing emissions and promoting energy security [12]. In 2023, more than 500 GW (GW)

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https://doi.org/10.1016/j.heliyon.2024.e29600
Received 28 December 2023; Received in revised form 2 April 2024; Accepted 10 April 2024
Available online 16 April 2024
2405-8440/

of renewable generation capacity are set to be added, setting a new record. Furthermore, one in five cars sold in 2023 is electric, which indicates a significant shift towards cleaner transportation technologies [13].

Despite its significant potentials, the renewable energy sector faces numerous challenges, including the intermittency of energy sources like solar and wind [14], high upfront costs [15], and complexities in energy storage and grid integration [16]. According to Ref. [17], these issues necessitate innovative solutions [18], and blockchain technology has emerged as a potential key player in this regard [19–23]. As a decentralized ledger technology, blockchain offers secure and transparent data storage and exchange without intermediaries [24–29]. Blockchain is known for its immutability and transparency, which are qualities that make it foundational to cryptocurrencies [30]. The application of blockchain is increasingly expanding to various sectors of the economy [31,32]. In the renewable energy sector, blockchain facilitates secure and transparent peer-to-peer energy trading [23,27,33], efficient management of supply and demand [34], and the tracking and verification of green energy sources [22,35–37]. The technology also automates operations through smart contracts, potentially reducing administrative costs and complexities [38]. The impact of blockchain in the energy sector is underscored by its market growth. The market value of blockchain in the energy sector was USD 278.0 million in 2019, and it is projected to reach USD 81,205.98 million by 2032, growing at a compound annual growth rate (CAGR) of 56.1 % from 2023 to 2032 [39].

In academia, the burgeoning interest in the interplay between blockchain technology and the renewable energy sector is reflected in numerous review studies, each focusing on different aspects and yielding varied findings. For example, Lampropoulos [40] underscores the pivotal role of blockchain in enhancing the security and digitalization of smart grids, which is crucial for achieving sustainability and sustainable development goals. Gawusu et al. [41] highlight the role of blockchain in the decentralization of renewable energy and underscore its potential to address challenges in the evolution of renewable energy and offer sustainable alternatives to fossil fuels. Andoni et al. [36] provide a systematic review of blockchain in the energy industry and explore its potential benefits and innovations, particularly in peer-to-peer (P2P) energy trading and Internet of Things (IoT) applications. Almutairi et al. [42] address the application challenges of blockchain in the renewable energy supply chain and emphasize the high investment cost as a significant barrier. In addition, Wang and Su [43] note an exponential increase in blockchain research within the energy sector, particularly since 2018, indicating a new cross-cutting research area. The authors show a focus on renewable energy and aim to solve its development bottlenecks and enhance its role as a replacement for fossil fuels. Yap et al. [44] highlight the importance of blockchain in distributed generation (DG) and stress its role in enhancing security, enabling P2P energy trading, and providing a decentralized energy management system.

Bao et al. [45] also review blockchain deployment in energy applications, ranging from energy management to electric vehicle-related applications, and discuss existing architectures, solutions, and security and privacy challenges. Junaidi et al. [16] systematically review blockchain applications in electric energy systems, focusing on demand response, electric vehicles, and decentralized energy management, and highlight the technology's potential to address the complexities of modern energy grids. Ahl et al. [46] explore blockchain-based P2P microgrids, analyzing potential challenges and suggesting practical implications for institutional development. Similarly, Hasankhani et al. [47] delve into blockchain applications in smart grids and categorize them in different areas including smart contracts, demand response, and energy trading, while highlighting opportunities and challenges. When it comes to bibliometrics, Ante et al. [48] utilize co-citation analysis to explore blockchain and energy, and identify distinct research streams and their impact. Cui et al. [49] use a bibliometric approach to analyze the rapid growth in research topics related to renewable energy and blockchain, focusing on areas such as energy system optimization and renewable energy trading.

Despite these comprehensive reviews, there is a discernible gap in studies specifically using co-word analysis to investigate the nexus of blockchain and the renewable energy sector. As a bibliometric method, co-word analysis provides insights into the structure and dynamics of scientific fields by analyzing the co-occurrence of keywords in literature. This approach is particularly valuable for exploring complex interactions and emerging trends in the blockchain-renewable energy interface, offering a nuanced understanding of this rapidly evolving research area. More specifically, the current study aims to address the following research questions.

1 What are the current status and prevailing research trends in the field of blockchain technology within the renewable energy sector?
2 What are the potential future research directions in the integration of blockchain technology with renewable energy?

A bibliometric analysis was conducted to objectively examine the current state of research in this area, present a conceptual structure of the field, and address these research questions. By responding to these questions, the current study makes a significant contribution to the literature by offering a comprehensive overview of the emerging trends and thematic shifts within the nexus of blockchain technology and renewable energy. This analysis identifies not only the prevailing research themes but also uncovers the gaps and opportunities for future investigation, thereby charting a path forward for scholarly exploration in this dynamic field. Importantly, our findings serve as a strategic roadmap for academicians and policymakers alike, highlighting critical areas where blockchain technology can be leveraged to enhance renewable energy systems. This is particularly relevant in the context of global efforts to achieve sustainable development goals, where our study underscores the potential of blockchain to facilitate the integration of renewable energy sources, enhance energy security, and promote environmental sustainability. By providing these insights, our research aids in the development of informed strategies that can accelerate the adoption of blockchain in the renewable energy sector, ultimately contributing to the global agenda for sustainable development.

2. Background

Conceptually, blockchain technology is essentially an encrypted database framework pivotal for the secure transaction of cryptocurrencies [50]. This technology underpins digital currencies like Bitcoin and Ethereum, providing a secure and transparent way to record transactions without the need for a central authority [51,52]. The concept of a decentralized ledger was introduced by an individual or group under the pseudonym Satoshi Nakamoto in 2008, primarily to support Bitcoin [50]. It has since evolved to support a wide range of applications beyond just cryptocurrencies. At its core, blockchain represents a collective and decentralized system that meticulously records digital transactions in a sequential manner using cryptographic techniques [53–56]. These techniques ensure the security and integrity of the data stored on blockchain. Each block in the chain contains a number of transactions, and every time a new transaction occurs on blockchain, a record of that transaction is added to every participant's ledger. This decentralized nature of blockchain technology is what makes it exceptionally secure and resistant to fraudulent activities [57].

The integrity of blockchain is such that once a transaction is recorded, it can only be amended with the consensus of the network's participants [42,51,58]. This means that every transaction is permanently recorded and viewable to anyone who has access to blockchain. As a result, this ensures greater transparency and control over transactions, making it an attractive option for industries like finance and healthcare, where transparency is crucial [31]. One of blockchain's most significant advantages is its ability to reduce economic inefficiencies by replacing complex bureaucratic procedures with simpler and more secure alternatives [59]. Traditional banking and financial systems often involve numerous intermediaries, each adding time and cost to transactions [60]. Blockchain technology can streamline these processes and reduce or even eliminate the need for intermediaries, leading to significant cost savings [36,61–63]. Furthermore, this aspect of blockchain ensures the integrity of data in environments where mutual trust might be lacking, thereby allowing for transactions to be conducted with greater confidence. In supply chain management, for example, blockchain can be used to create a permanent and transparent record of the journey of goods from manufacture to sale, reducing the likelihood of fraud and errors [64]. The technology's aptitude for automating transactions, eliminating intermediaries, and thus streamlining operations, makes it particularly beneficial for several applications beyond finance, including supply chain management, healthcare, and even voting systems [65–67].

In the context of the renewable energy sector, blockchain technology has garnered significant interest, particularly for its role in advancing the Internet of Energy (IoE) [60,68–70]. This concept emphasizes transparent and decentralized networks where individuals and businesses, known as energy prosumers, can actively participate in energy trading platforms [71–75]. The implementation of blockchain in the energy industry has notably supported the transition to sustainable practices and circular economy initiatives. One of the key areas where blockchain has made an impact is in electric e-mobility solutions [36,76–79]. The technology enables secure and efficient transactions for electric vehicle charging and billing, thereby facilitating the growth of the electric vehicle market [80]. Additionally, the technology promotes energy democratization and allows small-scale renewable energy producers direct access to the energy market [58,81–83]. This democratization enables these producers to sell excess energy, contributing to a more equitable and diversified energy landscape.

Blockchain's influence extends to the development of P2P energy trading platforms. These platforms allow for the direct trade of excess renewable energy between individuals and businesses, bypassing traditional energy intermediaries [84–87]. This direct trade leads to more efficient use of renewable energy and potentially lower costs for consumers [3]. Moreover, blockchain aids in implementing demand-response mechanisms. Through these mechanisms, consumers are incentivized to reduce or shift their energy usage during peak periods, which helps in balancing the grid and enhancing its efficiency. The technology also plays a crucial role in smart metering and grid management [88–91]. By providing a secure way to record and verify energy consumption data from smart meters, blockchain enhances transparency and trust in energy billing [92–94]. It also supports better grid management by efficiently tracking and distributing energy where it is most needed. In the realm of green certificates issuance and carbon trading, blockchain ensures the authenticity and traceability of green certificates [95–97]. These certificates verify that certain amounts of electricity are generated from renewable energy sources. Additionally, blockchain streamlines carbon credit trading by offering a transparent and tamper-proof system [98].

Several scholars highlight that blockchain offers significant benefits for the energy sector in different ways [16,27,48,49,68]. For example, the technology enables decentralized energy trading and supply and creates more resilient and efficient energy system where local generation and consumption can reduce grid strain and transmission losses [16,47]. Blockchain's application in automated control of energy and storage flows through smart contracts is equally important. These contracts automate complex transactions and operational processes, including the real-time balancing of supply and demand [36,99]. Finally, the secure recording of all business activities in the energy industry is a critical feature of blockchain. Its security features ensure that all transactions and operational data are recorded securely and immutably, which enhances transparency and trust among all stakeholders [22,100,101].

3. Academic knowledge dynamics

Bibliometric techniques are employed to uncover knowledge trends within scientific publications by synthesizing and analyzing bibliographic information gathered from academic articles [102,103]. As a particular approach within bibliometrics, co-word analysis hinges on the principle of co-occurrence, which is the simultaneous appearance of words within the same document [104,105]. This method facilitates the linking of literature content into a web of knowledge elements via networks formed by these co-occurring words [106]. It is a common practice for authors to select a set of keywords that best encapsulate their article's primary research theme. Utilizing these keywords, researchers can trace the conceptual framework of a study, construct thematic maps, and chart the evolution of a research area [107]. In our specific study, we employed co-word analysis to explore research themes and uncover the interconnections between blockchain technology and the renewable energy sector.

Co-word analysis utilizes the concept of co-occurrence analysis, which focuses on identifying entities that frequently appear together [108–110]. This analysis can involve various elements like keywords, references, or authors, offering insights into the cutting-edge developments in a field. The method involves quantifying how often terms appear together in scholarly articles, thereby determining the strength of their associations [111]. This approach helps in mapping out the scientific landscape. Specifically, co-word analysis considers keywords chosen by authors that co-occur in the abstract, keywords, or titles of the same publication [112]. These keywords form networks where they serve as nodes, and their co-occurrence in a publication creates a connection or edge in this network. Choudhury and Uddin [113] describe how repeated appearances of keyword pairs in various articles strengthen these network connections. The frequency of each term is represented by the node's size, while the thickness of the lines between nodes indicates the frequency of co-occurrence [114,115]. As Cobo et al. [116] point out, the end product of this analysis is a collection of clusters that symbolize groups of related textual data, essentially representing conceptual or semantic categories within the researched area.

The examination of research themes culminates with the creation of a strategic map or diagram, which visually depicts the topics studied [117]. This map categorizes topics based on their centrality and density [118]. Centrality indicates how strongly a particular cluster is connected to others, while density reflects the robustness of the connections among the terms within that cluster [116]. A cluster with high centrality is often seen as a focal point of research, signifying the relevance and impact of that topic in the broader research domain. Consequently, the positioning of a cluster on this map serves as an indicator of its strategic significance in the scientific field, reflecting both its internal coherence and its overall significance in the field under consideration [119].

Incorporating these dimensions, research themes are categorized within a two-dimensional framework based on their placement in specific quadrants, as illustrated in Fig. 1, following the methodology of Callon et al. [104].

- In Quadrant 1, which is characterized as peripheral and underdeveloped, the themes are in their infancy, not well-structured, and are considered marginal in the current scope of study.
- Quadrant 2 is defined as core and underdeveloped. This quadrant includes topics that, though currently not fully fleshed out, have potential to become central and influential in future research.
- Quadrant 3, known as core and developed, contains the key themes of the field. These are well-established and mature topics that are crucial to the structure and progress of the study area.
- Themes in Quadrant 4, labeled as peripheral and developed, are recognized for being well-developed but are moving towards less relevance due to their highly specialized nature.

As outlined by Lascialfari et al. [119], themes situated in the lower quadrants (1 and 2) are identified as niche areas due to their lower density, while those in the upper quadrants (3 and 4) are considered main or significant themes, marked by their higher density. This framework allows for the tracking of a theme's evolution within the field: a niche topic might ascend to a main category, maintain its niche status, or fade away over time, contingent on its progression towards greater density and centrality.

Considering that the evolution over time of a scientific field is influenced by changes in centrality and density, researchers can deduce the developmental stages of research topics within any field. Lascialfari et al. [119] have expanded upon the concept of a strategic map by incorporating the dynamic nature of research topics. They describe the life cycle of these topics through three distinct phases: 1) scaling-out, 2) scaling-up, and 3) scaling-down. The first phase, scaling-out, is characterized by an increase in centrality.

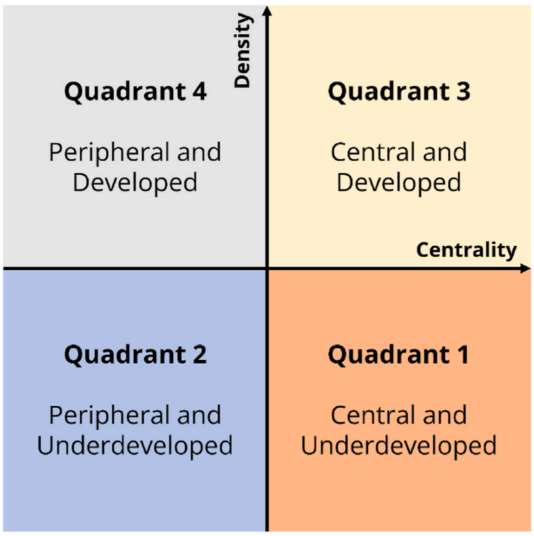


Fig. 1. Strategic diagram and cluster group characterization [119].

This phase occurs as the concepts or terms of a research topic gain broader acceptance and integration with other topics, marking the initial phase where the research gains external recognition and wider adoption in the scientific community. The scaling-up phase happens when a research topic grows in complexity and internal organization. This growth is indicated by a rise in density, which is seen as an increase in the connections among concepts within the topic cluster, leading to its transition from a niche to a mainstream topic. Finally, the scaling-down phase is observed when there is a decline in centrality, even though the topic maintains a high density. This phase signifies a reduction in the adoption of the topic's terms since they become less frequently used. Therefore, the life cycle of research topics is dynamically represented in a strategic map (Fig. 2). Additionally, if a promising cluster enhances its internal structure, the mainstream topics in quadrant 3, which are the driving forces of the field, expand, while themes that start to decline may shift to quadrant 4, indicating their reduced prominence. In essence, this dynamic strategic map offers an overview of a field's structure in terms of its temporal progression and illustrates how niche themes can evolve into mainstream topics.

The analysis of one strategic map might not offer a comprehensive understanding of research because a static representation fails to uncover the changing dynamics as research progresses. This limitation arises from the inability of a single map to fully capture the movement of research theme clusters across different quadrants over time. To effectively analyze the shifting positions of these clusters on the strategic map, it is essential to examine multiple strategic maps created at various time intervals. Fields of science that swiftly transition their niche clusters into major ones demonstrate greater overall development. Conversely, fields that lack this dynamism tend to receive less focus and remain as specialized clusters with comparatively lower levels of development.

4. Review methodology

Guided by Moher et al. [120], our article selection followed the PRISMA methodology, which represents a structured approach that ensures a systematic, clear, and reproducible synthesis of literature [121]. This method involves a four-stage process, including identification, selection, eligibility, and inclusion (see Fig. 3). Through this approach, relevant keywords were determined, and articles were methodically chosen for our analysis. The preference for the Web of Science (WoS) database is rooted in its comprehensive collection of validated knowledge from published scientific papers [122]. Different databases vary in their coverage of scientific disciplines, each with unique strengths and limitations [123]. Furthermore, merging data from various databases can introduce several inconsistencies in data analysis, especially for large article samples [124]. WoS stands out globally for academic research, offering extensive resources in citations, publications, impact indices, and other metadata crucial for bibliometric analysis [125,126]. Its widespread use across various knowledge fields [127–129] ensures a robust foundation for conducting an in-depth analysis of the thematic evolution in the field under study over time [123,130].

During the identification phase, to accurately curate the final collection of articles for analysis, we meticulously examined the most common keywords within the literature pertaining to blockchain technology and the renewable energy sector. This step was crucial to

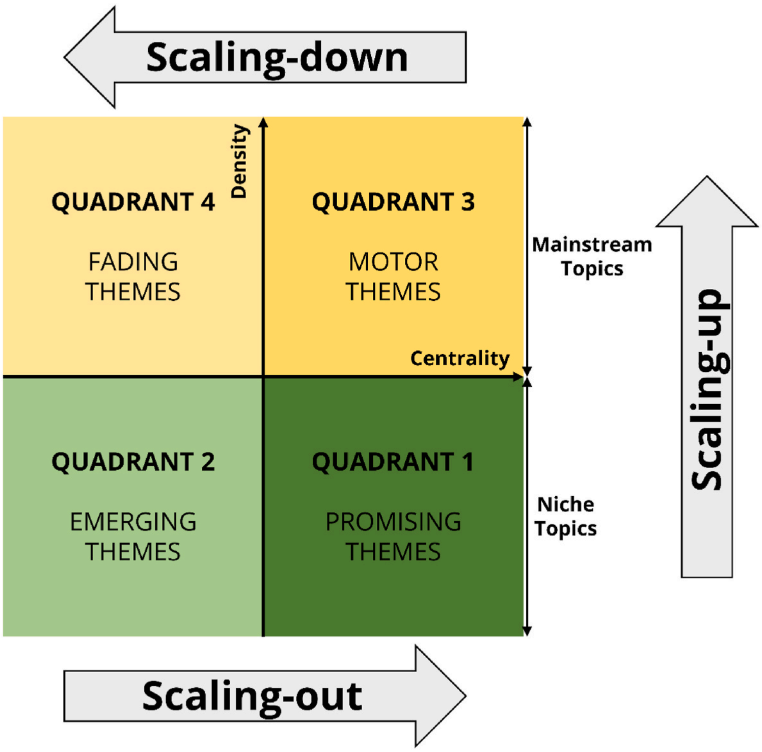


Fig. 2. Dynamic strategic map [119].

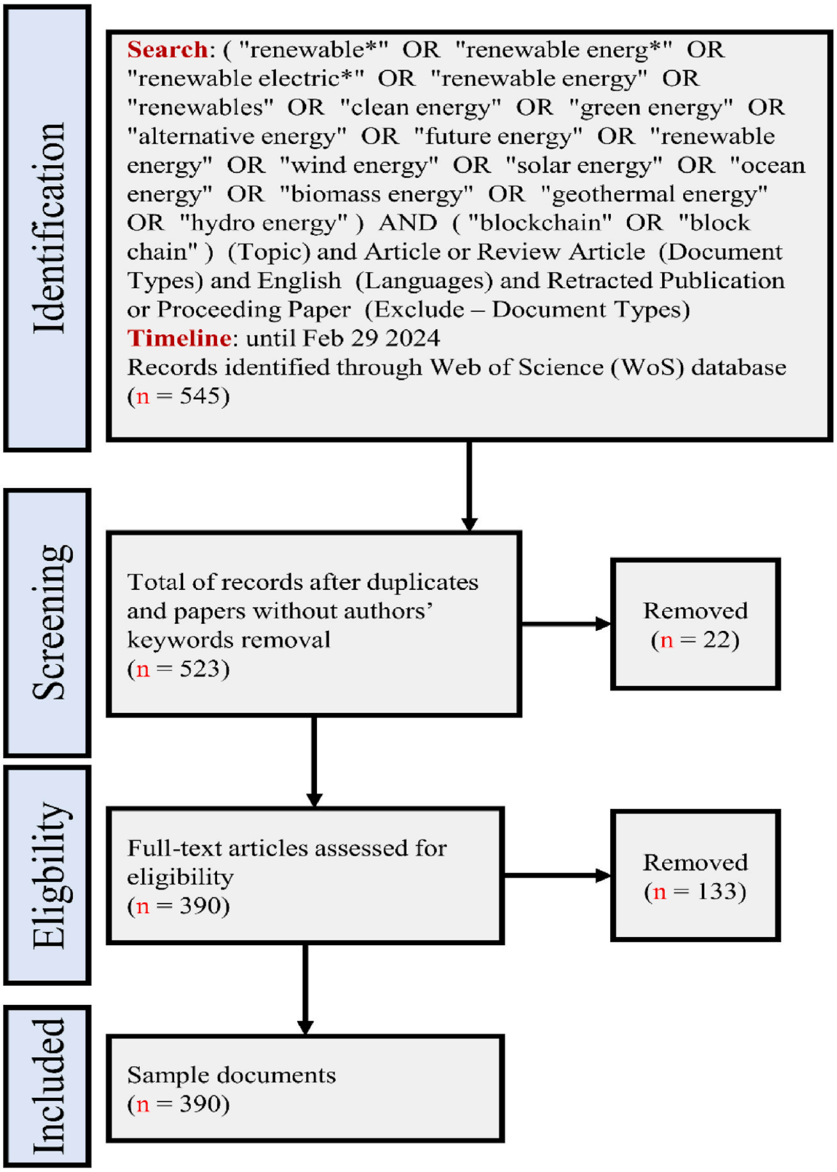


Fig. 3. Method for collecting articles in accordance with PRISMA guidelines.

ensure a precise and comprehensive search for the study topics. Using the WoS, a plain text file was generated for each theme, from which we extracted the keywords. Following the methodology outlined by Liu et al. [130], the final selection of articles was determined using specific keywords, Boolean operators, and advanced search parameters: TS= ("renewable*" OR "renewable energ*" OR "renewable electric*" OR "renewable energy" OR "renewables" OR "clean energy" OR "green energy" OR "alternative energy" OR "future energy" OR "renewable energy" OR "wind energy" OR "solar energy" OR "ocean energy" OR "biomass energy" OR "geothermal energy" OR "hydro energy") AND ("blockchain" OR "block chain"). To account for the various terminological variations in both fields, an asterisk was employed, capturing all potential derivatives of these terms. Consequently, the search yielded a set of 545 articles published from 2017 to the end of February 2024, which included relevant search terms in their titles, keywords, and abstracts. The next step involved standardizing the gathered database. We meticulously reviewed and removed duplicate articles, those not pertinent to our study area, and those lacking author keywords, resulting in a refined collection of 390 articles.

The bibliometric analysis was conducted using the Bibliometrix software [131], which is based on the R programming language. This software offers a user-friendly graphical interface through Biblioshiny, enabling the downloading of files in Excel format for further processing. With the support of Biblioshiny, we generated a file containing the keywords, which were then standardized and normalized. The software's functionality includes synonym usage and the removal of irrelevant words, facilitating the creation of refined.csv format Excel sheets suitable for our analysis.

Adhering to the guidelines provided by previous research [132], we developed a file for managing synonyms, which involved normalizing abbreviations (e.g., RES as renewable energy sources), plurals (e.g., microgrids as microgrid), derivations (e.g., electric vehicles, or EVS as EV), and words with similar meanings. Table 1 provides a summary of the characteristics of the sample, covering research papers from 2017 to the end of February 2024. This period reflects a notable annual growth rate of 47.24 %, with an average document age of 2.43 years. The growth rate underscores the burgeoning interest in the intersection of blockchain technology and renewable energy. The compilation consists of 390 documents sourced from 134 distinct outlets, including 223 articles, 97 articles with early access, 47 reviews, and 23 reviews with early access. These documents collectively cite 17,690 references, with an average of 26.5 citations per document. This signifies the significant influence and pertinence of this research domain.

In terms of authorship dynamics, there are 1409 authors contributing to the sample, with an average of 4.32 authors per document, suggesting a prevailing inclination towards collaborative research efforts. Among these contributions, 15 are single-authored documents, which illustrates the complex and multidisciplinary nature of integrating blockchain technology into the renewable energy sector. Additionally, the data reveal a considerable extent of international collaboration, with 43.08 % of the documents featuring international co-authorships.

Regarding the strategic map analysis, we conducted a static examination to capture the present state of research across the entire period covered by our sample (2017–2024). Additionally, we analyzed the strategic maps for three distinct time intervals: 2017–2019, 2020–2021, and 2022–2024. Given that this field of study is still emerging, the decision was made to segment the analysis by years rather than by the volume of publications. This approach was particularly relevant as the majority of the publications occurred in the last two years of the period under review.

5. Analysis of results

5.1. Descriptive analysis

Prior to delving into the discussion of the findings, a descriptive analysis is provided, starting with details pertaining to the citations and then addressing those related to the references. Regarding the progression of the literature, an observable exponential surge in the number of publications is highlighted in Fig. 4. Notably, there has been a substantial upswing in recent years, peaking with 76 articles in 2021, which represents a significant portion of the cumulative count. This was succeeded by a further increase to 111 articles in 2022, marking a notable escalation in the volume of literature on the topic. The slight decrease to 99 publications in 2023, and an early count of 15 in 2024, reflects the ongoing interest and research activity in this field, with the variations attributed to the timing of data collection and publication schedules.

The journals disseminating significant research on blockchain technology in the renewable energy sector include "Energies," "IEEE Access," "Sustainability," "Applied Energy," and "Renewable & Sustainable Energy Reviews," among others. "Energies" leads with 51 publications and an H-index of 15, accumulating 796 citations since 2017. "IEEE Access" follows closely with 43 publications, boasting an H-index of 19 and 1367 citations since 2018, indicating its substantial impact and the quality of research published. "Sustainability" and "Applied Energy" also play critical roles, with "Sustainability" having 19 publications and an H-index of 10 since 2018, and "Applied Energy" featuring 13 publications with an H-index of 12 in the same period. "Renewable & Sustainable Energy Reviews" adds to the discourse with 12 publications and an H-index of 8 since 2019. These journals are crucial for advancing research in blockchain

Table 1
Main bibliometric information about the selected sample.

Description	Results
Main information about data	
Timespan	2017:2024
Sources	134
Documents	390
Annual growth rate %	47.24
Document average age	2.43
Average citations per document	26.5
References	17690
Document contents	
Keywords plus (ID)	482
Author's keywords (DE)	1059
Authors	
Authors	1409
Authors of single-authored documents	15
Authors collaboration	
Single-authored documents	15
Co-Authors per document	4.32
International co-authorships %	43.08
Document types	
Article	223
Article; early access	97
Review	47
Review; early access	23

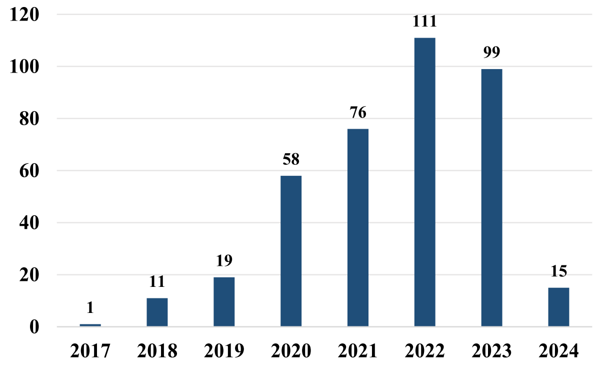


Fig. 4. Annual distribution of publications.

applications within the renewable energy field, as evidenced by their high H-indexes and total citations. This highlights their importance in disseminating high-impact research. Table 2 provides detailed information about these journals, underscoring their significant contribution to blockchain technology research in renewable energy.

The distribution of scholarly work on blockchain technology within the renewable energy sector, as represented in Fig. 5, adheres to Bradford's Law. This bibliometric principle posits that a core set of journals most frequently publish on a given topic and garner the majority of citations. These are categorized into three distinct zones reflecting their relevance and contribution to the field of study. Zone 1 consists of the most pivotal sources, with 138 articles representing the bulk of the literature and its impact. Zone 2 comprises 24 journals contributing 125 articles, accounting for approximately 32.05 % of the total number of publications, and signifying their moderate influence. Lastly, Zone 3 includes journals that less frequently feature articles on the subject, contributing 127 articles. This represents around 32.56 % of the total publications, emphasizing their peripheral role in the domain. The stratification into zones underscores the varying degrees of focus and impact journals have within the research landscape of blockchain in renewable energy.

The scholarly contributions to blockchain technology in the renewable energy sector are illuminated in Table 3, which showcases authorship and citation data. The table reveals the significant impact of individual authors in this evolving field. Leading in terms of publication volume are N Kumar with 7 publications and 355 citations, WQ Hua with 6 publications and 141 citations, and Y Zhang with 6 publications and 84 citations. Additionally, P Siano's contribution stands out with 5 publications, accumulating 272 citations. These top contributors, along with other notable authors listed in the table, collectively demonstrate a substantial impact on the research landscape of blockchain in renewable energy. Their work, as evidenced by the number of citations, has significantly influenced the direction and discourse within the academic community. The collective citations received by these authors also reflect the relevance and importance of their research contributions to the field.

To demonstrate the most influential research within the field of blockchain technology in the renewable energy sector, it is crucial to consider both the citations received within the sample (local citations) and the global citations (in the WoS database). These metrics offer insights into the impact and significance of the research among the scientific community. Table 4 highlights the most cited articles in our sample and showcases their profound contribution to the literature. These articles have collectively received 655 local citations and were published between 2017 and 2021. This range indicates the recency and relevance of research in this field.

The research field of blockchain technology in the renewable energy sector has been notably advanced by two significant contributions. The first [36], has achieved widespread recognition with 120 local citations and an impressive 919 global citations. This systematic review delves deeply into the potential and challenges of blockchain technology in the energy sector. Andoni et al.'s [36] work is distinctive for its comprehensive analysis of over 140 blockchain initiatives, ranging from peer-to-peer energy trading to IoT applications and decentralized marketplaces. The paper is particularly lauded for its dual focus: identifying technical challenges and potential drawbacks of blockchain in various energy applications, and presenting a detailed overview of current research and industry projects in these areas. In contrast, Mengelkamp et al. [133] offer a more focused approach by examining the application of blockchain

Table 2
Most relevant sources.

Source	H-index	Total citations	Number of publications	Starting year of publication
Energies	15	796	51	2017
IEEE Access	19	1367	43	2018
Sustainability	10	327	19	2018
Applied Energy	12	1433	13	2018
Renewable & Sustainable Energy Reviews	8	1353	12	2019
International Journal of Electrical Power & Energy Systems	9	378	11	2020
IEEE Internet of Things Journal	7	557	10	2019
Sensors	6	120	10	2020
Energy	5	185	8	2020
Journal of Cleaner Production	4	59	8	2021

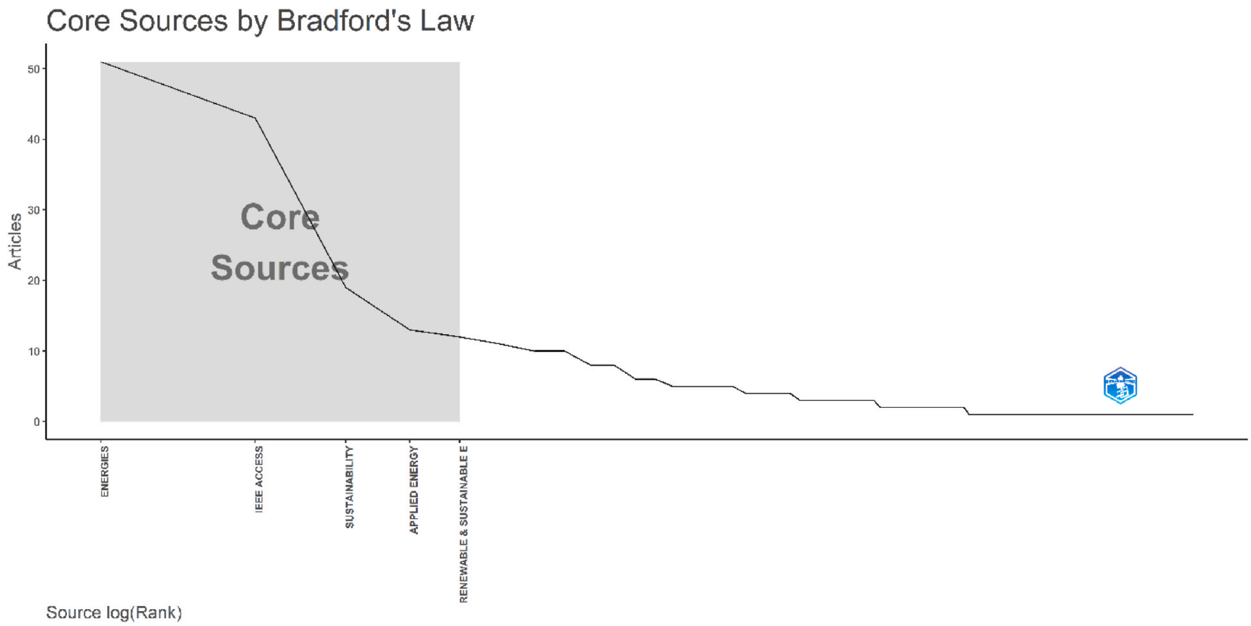


Fig. 5. Main journals according to Bradford's Law.

Table 3
Most productive and influential authors.

Author	H-index	Total citations	Number of publications
KUMAR N	6	355	7
HUA WQ	5	141	6
ZHANG Y	5	84	6
CUFFE P	3	30	6
JAVAID N	5	227	5
SIANO P	5	272	5
CALI U	4	45	5
WU Y	3	138	5
ALMOGREN A	4	194	4
GUERRERO JM	4	318	4
JIANG J	4	132	4
MENGELKAMP E	4	1277	4
SUN HJ	4	132	4
TANAKA K	4	263	4
TANWAR S	4	165	4
TSAO YC	4	125	4
WANG H	4	208	4
WEINHARDT C	4	1277	4
WU JZ	4	131	4
LI MC	3	48	4
MUYEEN SM	3	386	4
ONEN A	3	70	4
WANG LZ	3	48	4
ZHOU Y	3	26	4
CIOARA T	2	67	4
ZHANG C	1	42	4

in microgrid energy markets through the Brooklyn Microgrid project. The authors highlight the increasing integration of distributed renewable energy sources and the consequent challenges in maintaining energy generation and consumption balance. Both studies significantly contribute to the discourse on blockchain technology in renewable energy. These works collectively enhance our understanding of blockchain's role in the evolving landscape of renewable energy.

The research sample's citation of 17690 papers underscores the rich and diverse academic landscape surrounding blockchain technology in the renewable energy sector. Table 5 highlights the most frequently cited works and reveals that the core theoretical foundation of this research area is built on a relatively small yet influential set of papers. The fact that the top ten papers alone have amassed 716 citations indicates their pivotal role in shaping current understanding and research directions in this field. The

Table 4
Main publications in research on blockchain technology and the renewable energy sector.

Document	Year	Local Citations	Global Citations
[36]	2019	127	973
[133]	2018	105	833
[134]	2018	56	419
[135]	2019	41	222
[136]	2020	13	215
[137]	2019	30	210
[138]	2021	22	193
[139]	2020	20	183
[46]	2019	37	169
[140]	2018	20	164
[141]	2021	15	156
[142]	2019	31	143
[34]	2020	17	138
[143]	2019	10	134
[38]	2018	19	124
[144]	2017	17	116
[59]	2018	13	107
[145]	2020	29	104
[146]	2019	25	97
[43]	2020	8	94

Table 5
Top 10 most frequently cited references.

Cited References	Citations
[36]	127
[133]	105
[147]	86
[148]	65
[50]	62
[149]	60
[150]	57
[134]	56
[151]	49
[152]	49

predominance of influential review articles among the most cited papers highlights their importance in synthesizing and integrating existing knowledge. These reviews not only provide comprehensive overviews of the current state of blockchain applications in renewable energy but also identify gaps and propose new research trajectories. This concentration of citations in a handful of seminal papers reflects the evolving nature of this research area, where foundational works continue to guide and influence new studies and explorations.

In summary, the citation pattern within this research sample reflects both the depth and breadth of the field. It underscores the significance of key theoretical works in guiding the discourse while also pointing to a vast landscape of diverse, yet less recognized, scholarly contributions that collectively enrich the understanding of blockchain technology's role in renewable energy.

In blockchain technology research within the renewable energy sector, keyword analysis is essential. Out of 1059 unique keywords used 2676 times, a notable 138 keywords were used more than twice, indicating key research themes. In contrast, the majority of keywords, numbering 816, appear only once, pointing to a variety of specific topics in the field.

The most prevalent keyword is "blockchain" mentioned 312 times, which is unsurprising given its use in the search query that formed the basis of this literature analysis. "Smart grid" and "smart contract" also feature prominently, with 87 and 83 mentions respectively, highlighting critical areas of focus. The top 20 keywords, including "microgrid," "renewable energy," and "energy trade," account for 37.78 % of all keyword usage, reflecting both the concentrated and diverse nature of this research domain.

In discerning specific research themes within the domain of blockchain technology in renewable energy, the analysis focused on keywords beyond the central terms of "blockchain" and "renewable energy" used in the search query. Consequently, the keywords "smart grid" and "energy trading" emerged prominently, mentioned 87 and 50 times respectively, followed closely by terms such as "electric vehicle" and "IoT." Fig. 6 illustrates a keyword cloud, which visually represents the prevalence of these terms with more frequently used keywords appearing larger.

The emphasis on "smart grid" and "energy trading" underscores a significant interest in integrating blockchain technology with smart grid infrastructures and energy trading mechanisms. Keywords like "smart contracts" and "renewable energy sources" highlight the technological advancements and diverse energy sources being explored within this field. Additionally, "microgrids," "privacy," and "blockchain technology" are among the top keywords that reflects key aspects such as localized energy distribution systems, data security, and the foundational aspects of blockchain in this sector. The use of "peer-to-peer energy trading" and "electric vehicles" in the

Fig. 6. Wordcloud of keywords in blockchain and renewable energy research.

keyword analysis points to the evolving dynamics of energy exchange and transportation within the renewable energy landscape. This keyword analysis offers a comprehensive understanding of the research trajectories and technology integrations in the field of blockchain and renewable energy.

5.2. Research trends

The analysis of co-words within the research on blockchain technology in the renewable energy sector provides crucial insights into prevalent themes and interconnections between various concepts, which is instrumental in responding to the initial research inquiry. Fig. 7 delineates the co-word network, wherein the nodes symbolize distinct keywords, and the thickness of the lines connecting them

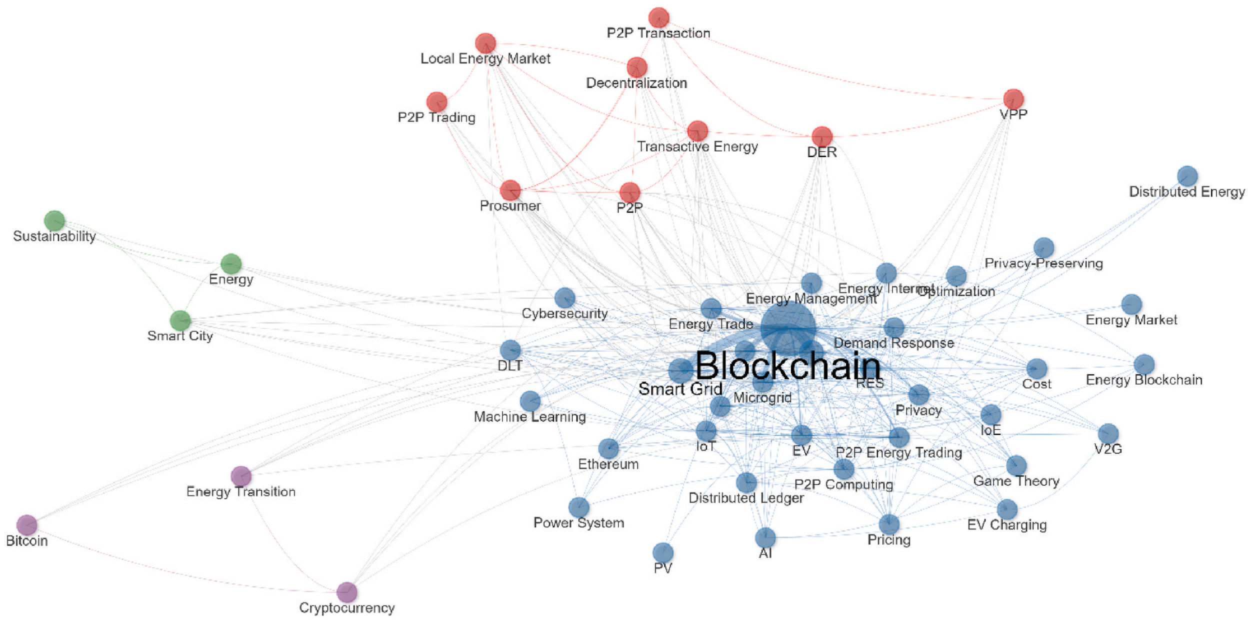


Fig. 7. Keyword co-occurrence network.

indicates the frequency of their co-occurrence. The node size signifies the prevalence of each term within the research body, while the line thickness correlates with the strength of the association between terms. The analysis has delineated four distinct clusters.

5.2.1. Blockchain-enabled innovations in smart energy systems

The blue cluster, emphasizing blockchain-enabled smart energy systems, illuminates the intersection of cutting-edge technologies reshaping the energy sector's landscape. At the forefront, 'blockchain' stands out as a critical innovation, facilitating secure, transparent, and decentralized frameworks for energy transactions and data management. The technology reinforces trust and operational efficiency within networks of energy producers, consumers, and prosumers [36,153]. 'Smart grid' and 'microgrid' technologies represent key components in transitioning towards more adaptive, self-sufficient energy networks that adeptly incorporate renewable energy sources and foster sustainability and enhanced energy management. These technologies are pivotal in realizing the potential of 'renewable energy' integration within modern energy systems, demonstrating a strong commitment to environmental stewardship and the effective utilization of green energy solutions [154,155].

The prominence of 'smart contracts' within this cluster underscores their role in automating transactions and enforcing agreements without intermediaries, thus ensuring transaction transparency and reliability. This technology is instrumental in the evolution of P2P energy trading platforms, such as 'p2p energy trading' and 'energy trade,' which advocate for a democratized energy distribution model. These platforms enable direct electricity exchanges among users, facilitating localized energy markets and supporting the decentralization ethos with 'distributed ledger technology' (DLT), which provides a secure and immutable record of transactions [156,157]. Additionally, 'demand response' initiatives and 'distributed energy resources' highlight the cluster's focus on creating responsive and interactive energy networks capable of adjusting to fluctuations in supply and demand. The concept of an 'energy internet' emerges as a vision for a fully interconnected energy exchange ecosystem, enabling seamless energy transactions across a broad network [38,158].

The integration of advanced technologies such as AI and 'machine learning' is recognized for their ability to optimize energy distribution and consumption, enhancing the overall efficiency of the energy systems. 'Game theory' is mentioned as a tool for strategic planning among diverse stakeholders in the energy market, ensuring competitive and cooperative dynamics lead to optimal outcomes [159]. In response to the increasing digitization of energy systems, the importance of 'privacy,' 'security,' and 'cybersecurity' is emphasized, addressing the critical need to protect sensitive data and ensure the integrity of the energy network against cyber threats. This focus on security aspects highlights the balancing act between embracing technological advancements and safeguarding the ecosystem against vulnerabilities [14,160]. In conclusion, the blue cluster captures the essence of a transformative period in the energy sector, driven by blockchain technology and its integration with smart grids, renewable energy, and digital security measures. This cluster showcases a roadmap towards a more sustainable, efficient, and secure energy future, underpinned by technological innovations that promise to redefine how energy is produced, distributed, and consumed.

5.2.2. Decentralized energy trading and markets

The red cluster, identified as "Decentralized Energy Trading and Markets," showcases the transformative potential of P2P models and decentralized frameworks in the renewable energy domain. This cluster emphasizes the significant shift towards more inclusive and participatory energy systems, where the roles of consumers and producers blur into the concept of 'prosumers.' These prosumers not only consume energy but also produce and sell it back to the grid or within local markets, embodying a key aspect of modern energy ecosystems [161]. The term 'transactive energy' within this cluster captures the essence of utilizing advanced economic and control mechanisms to optimize the balance between energy supply and demand across the network. This approach not only enhances the efficiency of energy distribution but also empowers consumers to play an active role in energy management processes. 'P2P trading' and 'P2P transactions' stand out as pillars of this cluster, highlighting the evolution towards systems where energy transactions occur directly between individuals without the need for traditional intermediaries. This P2P exchange model promotes a more resilient and flexible energy system, capable of adapting to changing demands and incorporating renewable energy sources more effectively. The concept of 'decentralization' underscores the movement away from centralized energy production to a more distributed system where energy generation and consumption points are spread across the network. This shift is critical for integrating renewable energy sources, such as solar and wind, which are inherently variable and distributed geographically. 'Distributed Energy Resources (DER)' and 'Virtual Power Plants (VPP)' further enrich the cluster's narrative by indicating the integration of distributed energy assets that can be managed collectively to support the grid while providing benefits to individual sites. VPPs, for instance, aggregate the capacities of multiple DERs to behave as a single power plant, thereby enhancing the reliability and flexibility of the power supply. Lastly, 'local energy markets' represent a microcosm of the broader shift towards decentralization, enabling localized energy generation, consumption, and trading. This fosters community resilience, energy independence, and the efficient use of local renewable energy resources. Overall, the red cluster vividly illustrates a future energy landscape marked by decentralized networks, empowered consumers, and a greater reliance on renewable energy sources. This vision aligns with global sustainability goals and the transition towards more adaptive, resilient, and environmentally friendly energy systems [16,47,162].

5.2.3. Sustainability and financial innovation in energy systems

The fusion of sustainability with financial innovation within the realm of energy systems, particularly through the adoption of smart cities and blockchain finance, heralds a groundbreaking approach to navigating the intertwined challenges of urban evolution and environmental preservation. The ensemble of 'smart city,' 'energy,' and 'sustainability' within the green cluster epitomizes the strategic integration of renewable energy solutions and energy efficiency into urban development. This paradigm is underscored by blockchain technology's capacity to refine and secure energy distribution within the dynamic framework of smart urban infrastructures [33]. This methodology not only aims to ameliorate urban living quality but also aligns with overarching sustainability objectives by mitigating environmental impacts and endorsing renewable energy sources.

Concurrently, the purple cluster's narrative on 'cryptocurrency,' 'energy transition,' and 'bitcoin' illuminates the financial innovation's pivotal role, particularly through blockchain technology, in revolutionizing funding mechanisms within the renewable energy domain. Blockchain's intrinsic attributes of decentralization, security, and transparency carve out novel pathways for investments and financing in renewable energy endeavors. Cryptocurrencies and digital tokens emerge as instruments for executing secure, transparent, and straightforward transactions, thus fostering a more democratic and efficient financial model for sustainable energy projects [36,163–165]. This financial ingenuity is indispensable in championing the energy transition, necessitating substantial investments to pivot from conventional fossil fuels to renewable energy sources. The amalgamation of these clusters signals a comprehensive strategy towards erecting energy frameworks that are not only environmentally sustainable but also economically sound and technologically forward-thinking. The implementation of smart city innovations for optimizing energy consumption, coupled with blockchain-based financial novelties, paves a promising avenue towards realizing sustainability in urban development and energy finance [166–171]. This integrated modality ensures that advancements in urban infrastructure and renewable energy are complemented by pioneering financial mechanisms, thereby facilitating a holistic shift towards sustainable and intelligent urban ecosystems.

The comprehensive analysis of research topics within the domain of blockchain technology in the renewable energy sector is visually encapsulated through the strategic diagram, which illustrates the significance of each topic based on its density and centrality metrics. This analytical approach facilitates the categorization of topics into distinct quadrants, as depicted in Fig. 8. Our findings indicate a total of 17 research themes. Among these, 8 have been identified as niche themes, characterized by their specialized focus and are situated in the lower quadrants of the diagram. In contrast, the remaining 9 themes are classified as main streams, signifying their broader relevance and prominence in the field, and are positioned in the upper quadrants.

The first quadrant in our strategic analysis, focusing on blockchain technology in the renewable energy sector, emphasizes two key themes: 'renewable energy certificates (RECs)' and 'peer-to-peer (P2P) trading'. The study by Fu et al. [172] introduces a blockchain-based approach for trading RECs, aiming to foster a low-carbon community of active energy agents (AEAs). This approach leverages blockchain oracles and smart contracts to streamline and decentralize REC transactions, aligning seamlessly with the 'renewable energy certificate' theme. On the other hand, Cali et al. [173] delve into the cybersecurity facets of REC trading within a blockchain framework. This study highlights the critical role of distributed ledger technology in ensuring the security and scalability of REC transactions, which represent a key concern in the increasingly digital energy landscape. This aligns with the 'renewable energy certificate' theme and emphasizes the importance of secure and reliable trading mechanisms. Together, these studies showcase the innovative potential of blockchain in revolutionizing 'renewable energy certificates' and 'P2P trading', underlining their growing importance in the field of renewable energy.

Quadrant 2 delineates topics that are poised to evolve into major themes within the realm of blockchain technology in the renewable energy sector. This quadrant highlights blockchain as the most prominent theme, with a significant 262 mentions. It stands as a testament to the technology's central role in enhancing transparency and efficiency in energy transactions and supply chain management [48]. Simultaneously, the theme of 'Energy' emerges with 9 references, encapsulating the broad spectrum of renewable

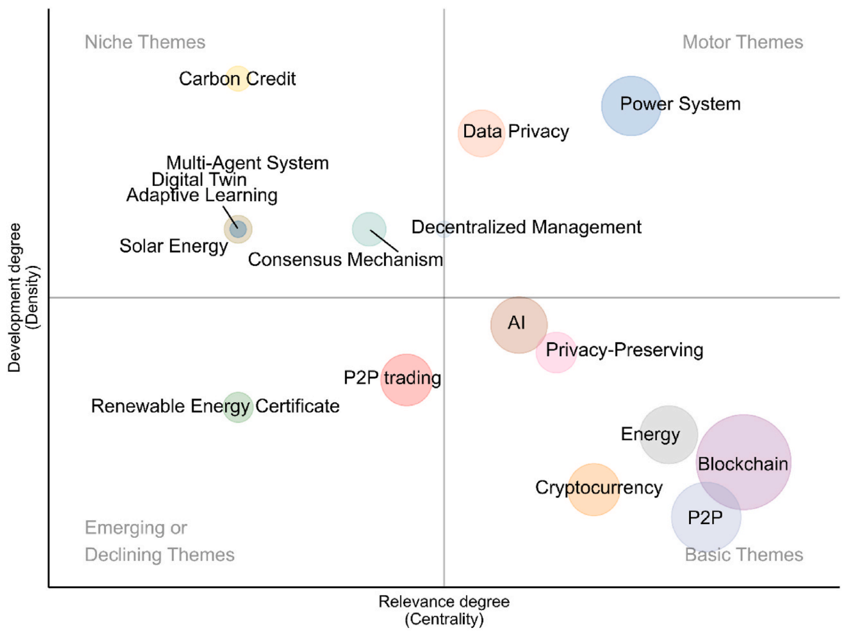


Fig. 8. Strategic diagram: Trends in blockchain and renewable energy research.

energy, from its generation to distribution. The intersection of blockchain technology in this context, as discussed in the academic literature, points towards transformative impacts on smart grids and decentralized energy systems. 'Cryptocurrency', matching 'Energy' with 9 mentions, underscores its growing relevance in the sector. The integration of cryptocurrencies in energy trading platforms, as reviewed in the works of Andoni et al. [36] and Ghorbanian et al. [165], illustrates a trend towards more fluid transactions in energy markets, with blockchain as the backbone for security and efficiency. Peer-to-Peer (P2P) Systems, noted 8 times, signify a shift towards decentralized energy networks, where blockchain facilitates energy trade among users.

The focus on 'Privacy-Preserving Techniques', with 4 mentions, brings to light the growing importance of data security in energy transactions. The potential of blockchain in enhancing privacy and securing energy data exchanges is a critical focus area [174,175]. Lastly, 'Artificial Intelligence (AI)', with 5 references, is gaining traction at the intersection of blockchain in the energy sector. As detailed in the literature [100,176], AI and blockchain together are spearheading the development of intelligent energy management systems. These systems aim to optimize renewable energy distribution and consumption, marking a significant advancement in energy management. In essence, these themes collectively paint a picture of a burgeoning trend towards integrating blockchain technology in the renewable energy sector. The focus is on fostering a more efficient, secure, and decentralized energy landscape, leveraging the synergies between advanced technologies.

The third quadrant of the strategic map illuminates key themes that are currently steering research and development efforts. These themes are specifically power system, data privacy, and decentralized management. The theme of 'power system' is increasingly significant, and it reflects the sector's push towards incorporating blockchain technology to boost the efficiency and sustainability of power systems. Representative studies, such as those proposed by Andoni et al. [36] and Ahl et al. [46], suggest that blockchain could be a game-changer in the way power is distributed and managed. This could open new avenues for optimizing the grid and seamlessly integrating renewable energy sources. The importance of 'data privacy' is escalating, especially as blockchain technologies become more prevalent in the energy sector. Blockchain's inherent security and transparency features make it an ideal solution for safeguarding sensitive information in energy transactions and operations. Representative studies [3,177,178] highlight the growing imperative for solid data protection strategies in an increasingly digitalized energy framework. Notably, 'decentralized management' stands out as a key trend, occupying a space that intersects both established methodologies and emerging themes. The potential of blockchain to revolutionize decentralized management of energy systems is underscored in the academic literature. This concept emphasizes a shift towards energy systems managed in a decentralized fashion, utilizing blockchain to bolster their resilience and adaptability [160,179].

The fourth quadrant of the strategic map highlights specialized themes or those on the verge of diminishing relevance. This quadrant is particularly insightful as it sheds light on niche areas of research that have either peaked in interest or are evolving into more refined areas of study. Within this quadrant, the theme of 'Consensus Mechanism' emerges as a significant area of focus. As the backbone of blockchain technology, consensus mechanisms are crucial in ensuring the integrity and reliability of distributed ledgers. Scholars agree that while traditional consensus mechanisms are well-researched [3], there is a shift towards more energy-efficient and scalable alternatives, especially pertinent in the renewable energy context [180].

The 'Carbon Credit' theme highlights the application of blockchain in environmental sustainability, particularly in tracking and trading carbon emissions. In this regard, several studies reflect the evolving nature of this theme, where blockchain is seen as a potential game-changer in enhancing the transparency and efficiency of carbon credit systems [36,98]. 'Solar Energy', with 5 mentions, underscores the integration of blockchain in optimizing solar energy production and distribution. This theme, explored in several studies [14,181,182], indicates a growing interest in using blockchain to manage and record solar energy transactions, making solar

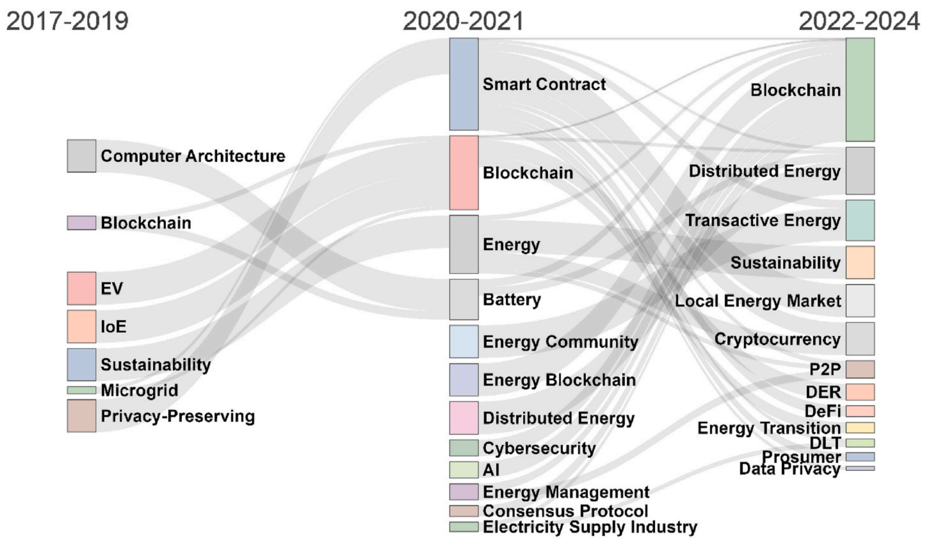
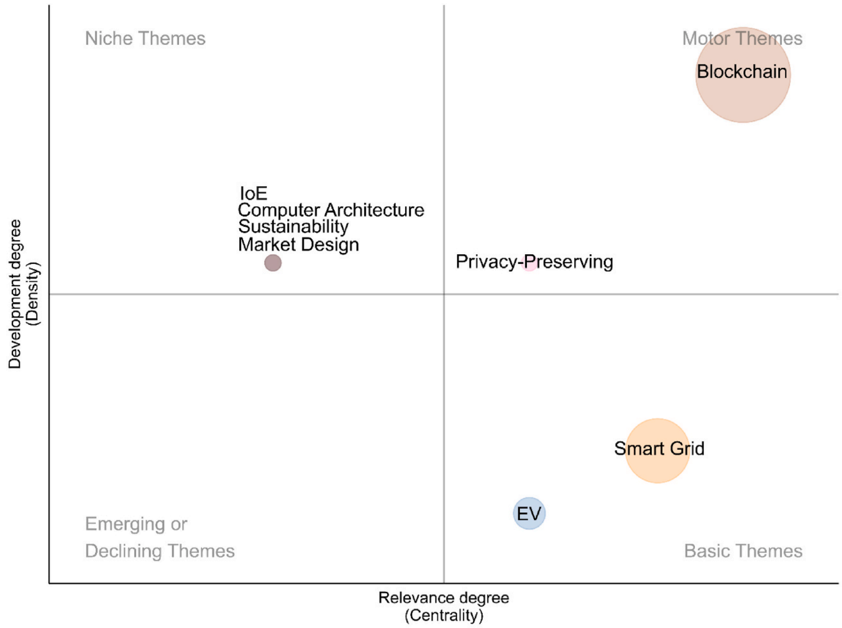
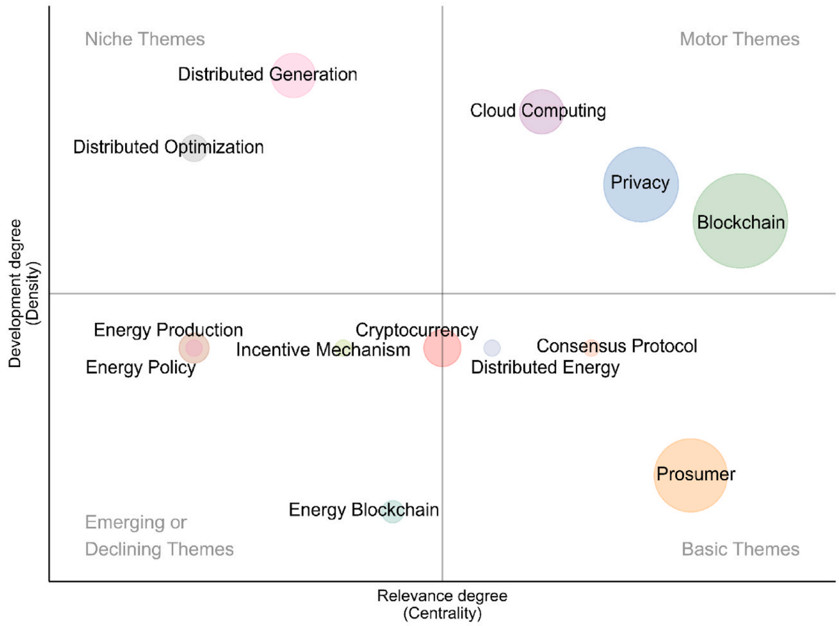


Fig. 9. Thematic evolution.

energy systems more efficient and user-friendly. The 'Multi-Agent System' theme, noted 4 times, relates to the use of blockchain in managing complex systems involving multiple actors or components. Researchers suggest that blockchain can significantly enhance the coordination and efficiency of multi-agent systems in the renewable energy sector [183–185]. The frequency of 'Adaptive Learning' highlights the use of blockchain in creating dynamic and responsive learning systems within the energy sector [30,186]. This topic explores how blockchain can facilitate adaptive and intelligent learning mechanisms for managing energy resources. Lastly, the inclusion of 'Digital Twin' illustrates the nascent application of blockchain in creating virtual replicas of physical energy systems. Prior studies point to an emerging trend where blockchain could play a role in enhancing the accuracy and efficiency of digital twins in

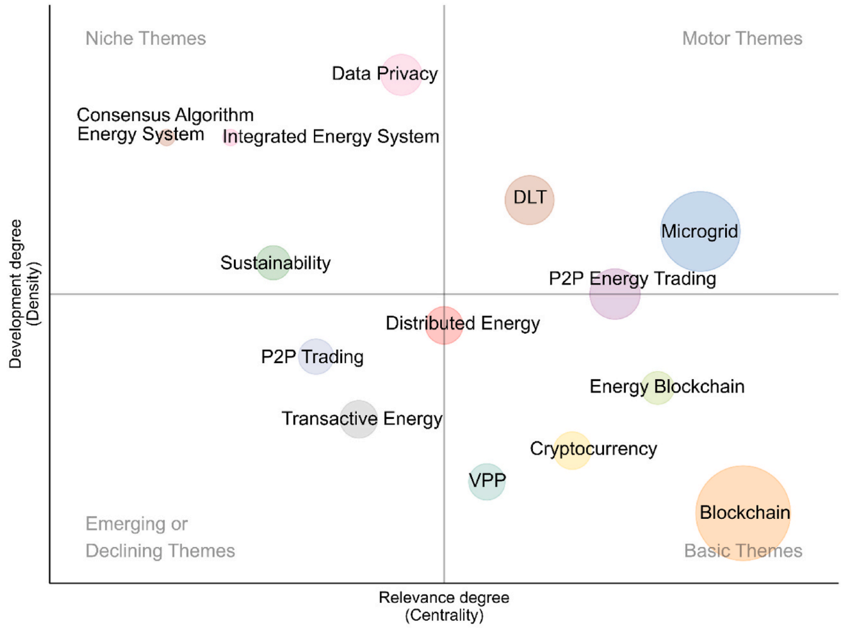


a. Dynamic strategic map of blockchain research in the renewable energy context (2017-2019)



b. Dynamic strategic map of blockchain research in the renewable energy context (2020-2021)

Fig. 10. aDynamic strategic map of blockchain research in the renewable energy context (2017–2019) Fig. 10b. Dynamic strategic map of blockchain research in the renewable energy context (2020–2021) Fig. 10c. Dynamic strategic map of blockchain research in the renewable energy context (2022–2024) Fig. 10. Dynamic strategic map of blockchain research in the renewable energy context.



c. Dynamic strategic map of blockchain research in the renewable energy context (2022-2024)

Fig. 10. (*continued*).

renewable energy systems [155,179,187].

The thematic evolution in the field of blockchain technology within the renewable energy sector between 2017 and 2023 is effectively illustrated through a Sankey Diagram (Fig. 9). This diagram offers a visual representation of the shifting focus of research and development across three distinct periods, highlighting the continuity and emergence of various themes [188,189]. In the 2017–2019 period (Fig. 10a), the diagram reflects themes such as 'Computer Architecture', 'Blockchain', 'Electric Vehicles', 'Internet of Energy', 'Sustainability', 'Microgrid', and 'Privacy-Preserving'. These themes indicate an early focus on integrating blockchain with fundamental aspects of energy systems and sustainability [98,190,191]. Moving to the 2020–2021 period (Fig. 10b), the diagram expands to include themes like 'Smart Contract', 'Energy', 'Battery', 'Energy Community', 'Energy Blockchain', 'Distributed Energy', 'Cybersecurity', 'AI', 'Energy Management', 'Consensus Protocol', and 'Electricity Supply Industry'. This expansion reflects a broadening of the scope. These years show an increased emphasis on digital technology, AI, and innovation, tying these elements to environmental sustainability and decision-making processes.

For the 2022–2024 period (Fig. 10c), the focus narrows down to themes like 'Blockchain', 'Distributed Energy', 'Transactive Energy', 'Sustainability', 'Local Energy Market', 'Cryptocurrency', 'P2P', 'DER' (Distributed Energy Resources), 'DeFi' (Decentralized Finance), 'Energy Transition', 'DLT', 'Prosumer', and 'Data Privacy'. This period highlights the growing importance of Industry 4.0 technologies in developing sustainability within the energy sector. Key studies for this period include Akkaoui et al. [160], Strielkowski et al. [192], Khurbani and Alam [162], which discuss the role of blockchain in facilitating sustainable energy operations and transitions. Throughout these periods, certain themes like 'Blockchain' and 'Sustainability' remain consistently relevant, underlining their central importance in the sector. The evolving themes across these periods reflect the dynamic nature of research in blockchain technology and its applications in renewable energy and emphasize a gradual shift from foundational concepts to more specialized and advanced topics like transactive energy and decentralized finance.

The dynamic thematic map provides a comprehensive overview, illustrating how the focus areas have evolved over time. This evolution can be traced through three distinct periods, each marked by a shift in priorities and advancements, reflecting the sector's growing complexity and integration of blockchain (see Fig. 10). Between 2017 and 2019, the initial phase of integration, blockchain technology emerged as a foundational driver. This period was crucial for laying the groundwork for future developments, with smart grids and EVs serving as basic themes. These early years were characterized by explorations into how blockchain could revolutionize energy distribution and consumption. Additionally, niche themes like computer architecture, market design, the Internet of Energy (IoE), and sustainability hinted at the broader potential impacts of blockchain in the energy sector.

The years 2020–2021 marked an expansion and integration phase. During this period, blockchain continued to hold prominence but was now seen in conjunction with emerging concerns around privacy and cloud computing. This shift highlighted a move towards solutions that were not only innovative but also secure and scalable. The basic themes evolved to include prosumer models, consensus protocols, and distributed energy, indicating a trend towards decentralized energy systems. Cryptocurrency also began to intersect with these themes, signifying an intriguing blend of the financial and energy sectors. The niche themes of distributed generation and optimization underscored a transition towards more user-centric energy models. Furthermore, the emerging themes of energy-specific blockchain applications, incentive mechanisms, and energy policies, along with the declining focus on energy production, indicated a maturation of the sector.

The period from 2022 to 2024 marks a significant shift towards specialization in the renewable energy sector, with Distributed Ledger Technology (DLT), microgrids, and peer-to-peer (P2P) energy trading at the forefront. These motor themes underscore a deeper integration of blockchain into energy systems, enhancing efficiency and direct transactions. Basic themes such as blockchain, cryptocurrency, energy blockchain, and virtual power plants (VPPs) continue to underpin this evolving infrastructure, facilitating secure and decentralized energy exchanges. Meanwhile, niche themes like data privacy and consensus mechanisms highlight the sector's focus on security and reliability. Emerging trends such as P2P trading and transactive energy reflect the industry's move towards more dynamic and regulated energy markets, showcasing a commitment to innovation and environmental sustainability in the face of evolving technological landscapes.

6. Discussion

The exploration of blockchain technology in the renewable energy sector reveals a dynamic and evolving landscape according to research trends and developments. This investigation has employed a combination of bibliometric analysis and thorough examination of selected academic papers, providing a comprehensive overview of the current state and future directions in this interdisciplinary field.

Our first research question aimed to uncover the prevailing research trends at the intersection of blockchain technology and renewable energy. The bibliometric analysis proved instrumental in dissecting the key terms, concepts, and their interrelations within the scholarly literature. This analytical approach not only highlighted the dominant trends but also spotlighted emerging topics poised for significant impact.

The surge in publications, especially in key journals, underscores a pronounced academic and industry interest in the convergence of blockchain technology and renewable energy. This observation aligns with Guwusu et al. [41], who underscored blockchain's role in decentralizing renewable energy, and Andoni et al. [36], who explored its benefits and innovations, particularly in P2P energy trading and IoT applications. Similarly, our study identifies an exponential growth in blockchain-related research within the energy sector, echoing Wang and Su [43], who noted a significant increase in research output since 2018, emphasizing renewable energy and its role in supplanting fossil fuels. However, this proliferation of literature also introduces challenges in maintaining research quality and novelty. According to Bradford's law, the concentration of research within certain journals suggests a focus of study within specific academic circles. While this can deepen field-specific knowledge, as our findings suggest, it may also result in a homogeneity of research approaches, mirroring concerns raised by Bao et al. [45] regarding blockchain deployment in energy applications. To counteract this, we propose, akin to Ahl et al. [46] and Hasankhani et al. [47], that diversifying publication venues and encouraging interdisciplinary research could mitigate risks associated with this concentration, fostering innovation and broadening the understanding of blockchain applications in renewable energy. Moreover, our analysis highlights the significant contributions of leading authors in the field, echoing Cui et al. [49], who utilized bibliometric analysis to delineate research trends and impacts. This underscores the pivotal role individual researchers play in shaping the discourse, suggesting that while collective academic output is growing, the influence of prominent scholars remains substantial in directing research trajectories and thematic focuses.

The focus on blockchain's application in renewable energy has predominantly centered on its technical and economic aspects. There is a need for more critical analyses that also consider the socio-political, ethical, and environmental implications of integrating blockchain into energy systems. For instance, while blockchain can enhance the efficiency of energy systems, it also comes with a significant energy consumption and environmental footprint [193–195], which must be critically assessed in the context of renewable energy goals. Lastly, the practical implementation of research findings in real-world scenarios remains a crucial aspect. The transition from theory to practice involves numerous challenges, including regulatory hurdles, market acceptance, and technological limitations. Collaborations between academia, industry, and policymakers are essential to bridge this gap and ensure that the advancements in blockchain technology can be effectively utilized to foster a more sustainable and efficient renewable energy sector.

The co-word analysis of blockchain in renewable energy not only corroborates the findings of Ante et al.'s [48] study on the technological integration in energy systems but also expands upon their identified themes. The first theme, focusing on blockchain's pivotal role in developing smart, secure, and decentralized energy systems, aligns with the insights provided by Wu and Tran [196], who emphasized the transformative potential of blockchain in achieving energy sustainability. Unlike Wu and Tran [196], however, our analysis boldly ventures into the specifics of incorporating technologies like smart grids and AI, underscoring a nuanced understanding of how these integrations enhance sustainability and efficiency.

Similarly, the importance of privacy and security in energy transactions and the facilitation of P2P energy trading through smart contracts echo the observations made by Li et al. [197], albeit with a more pronounced emphasis on the democratization of energy distribution. This shift towards responsive and democratized energy systems is further elaborated in our analysis, offering a more detailed examination. The second theme's focus on decentralized energy trading and the emergence of 'prosumers' parallels the findings of Mehdinejad et al.'s [198] investigation into decentralized energy markets. However, our study introduces a novel perspective by highlighting the role of virtual power plants and community-focused energy landscapes. Moreover, our discussion on the last two clusters significantly advances the discourse initiated by Samuel et al. [199] on the fusion of sustainability and financial innovation within smart cities. While Sumel et al. [199] briefly touched upon the potential of blockchain in renewable energy financing, our analysis provides a more comprehensive exploration of how digital currencies can fund renewable projects, thereby supporting the transition to sustainable energy sources.

Key themes identified from our strategic map analysis, notably 'renewable energy certificates (RECs)' and 'peer-to-peer (P2P) trading,' align with the findings of Liu et al. [22], who also emphasized the growing importance of decentralized energy systems.

However, our study extends beyond their work by highlighting the integral role of blockchain in enhancing transparency and efficiency, a detail that Rejeb et al. [200] analysis only touched upon superficially. The prominence of 'blockchain' in our analysis reaffirms its critical role in energy transactions and supply chain management. Yet, unlike the prior literature, our study delves deeper into the implications of blockchain in energy markets, particularly through the lens of 'Cryptocurrency' and 'Peer-to-Peer (P2P) Systems', showcasing a broader scope of blockchain's impact on decentralized energy networks. Furthermore, the emphasis on power systems, data privacy, and decentralized management in our research parallels the themes explored by Dehghani et al. [201], who discussed blockchain's potential in power system optimization and data security. Nevertheless, our analysis presents a more nuanced examination of these themes, particularly in highlighting specialized or diminishing themes such as 'Consensus Mechanism' and 'Carbon Credit'. This aspect of our study introduces a new dimension to the conversation about efficient blockchain consensus mechanisms and blockchain's role in carbon emissions trading.

The thematic evolution captured in the Sankey Diagram from 2017 to 2024 illustrates a discernible shift within the blockchain and renewable energy sector, from foundational to more advanced and specialized areas. This progression highlights the sector's growing sophistication and the deeper integration of blockchain technology. Our observations resonate with the analysis presented by Ante et al. [48], who noted an early focus on basic blockchain applications in energy systems. However, unlike their study, our analysis reveals a more pronounced transition towards specialized topics like transactive energy and decentralized finance, indicating a maturation of the field. Similarly, the work of Lampropoulos [40] underscores the initial emphasis on smart grids and electric vehicles, but our findings extend this trajectory, showcasing a sector now gravitating towards P2P trading, data privacy, and the inclusion of green bonds. This nuanced evolution reflects an industry increasingly aimed at developing practical, scalable, and environmentally responsible energy solutions, marking a significant advance over the preliminary observations of these two studies.

7. Conclusions

In the exploration of blockchain technology within the renewable energy sector, the current study highlights its significant transformative potential. The methodological approach, employing bibliometrics to analyze 390 journal articles sourced from the Web of Science, offers a clear snapshot of the current state and future trajectory of this interdisciplinary area. This analysis is grounded firmly in the data from these articles, enabling us to identify key themes and insights that point toward valuable directions for future research. By rigorously examining the content and context of these publications, we have distilled the essence of blockchain's growing role in renewable energy, reflecting both its current impact and its promising future.

7.1. Research implications

The transformative potential of blockchain technology in the renewable energy sector is becoming increasingly clear, offering groundbreaking solutions for decentralized energy trading, enhancing system efficiency, and promoting transactional transparency. The surge in relevant academic publications reflects a robust interest and recognition of blockchain's potential in this domain. Through its bibliometric approach, the current study has begun to address this gap and identify themes and emerging trends. These include the integration of blockchain with smart grids, electric vehicles, and its role in facilitating sustainable energy solutions in smart cities. The identified themes have led to several suggestions for future research. These include a need for deeper exploration into the socio-political, ethical, and environmental implications of blockchain in renewable energy. There is also a call for research into the practical implementation of blockchain technology, addressing challenges such as regulatory hurdles, market acceptance, and technological limitations. Moreover, the review underscores the necessity for more interdisciplinary research, integrating insights from fields such as economics, sociology, and environmental science, to develop a more holistic understanding of blockchain's role in renewable energy. This is particularly important in addressing broader sustainability goals and ensuring that blockchain technology contributes positively to the global energy transition. In sum, while the review has provided significant contributions to our understanding of blockchain in the renewable energy sector, it also opens up new avenues for research and highlights the need for more comprehensive and multidisciplinary approaches. As the field continues to evolve rapidly, ongoing research must adapt to these changing dynamics, ensuring that the potential of blockchain technology is fully realized in the pursuit of a more sustainable, efficient, and equitable energy future.

7.2. Research limitations

Despite the valuable insights garnered from our review, it is crucial to acknowledge the inherent limitations of our research methodology. Primarily, our reliance on bibliometric indicators and the exclusive selection of articles from the Web of Science database could introduce a selection bias. This methodology may inadvertently exclude pertinent studies published in other scholarly databases or within the grey literature, which could offer additional perspectives or contradict our findings. Moreover, while the bibliometric approach is adept at outlining the broader landscape and identifying prevailing trends within the field, it may fall short in capturing the intricate details and nuanced understanding of individual research articles. It also might not fully delineate the complex interactions among various themes identified throughout the study.

Furthermore, the analysis, focused on journal articles up until the end of February 2024, might not reflect the very latest developments and emerging trends in the rapidly evolving blockchain and renewable energy sectors. This temporal cutoff could potentially omit significant advancements or shifts in research focus that occurred shortly after this period. Additionally, the study's scope, concentrating on blockchain technology within the renewable energy sector, limits the exploration of blockchain's applicability and implications in adjacent fields or industries that could offer complementary insights or multidisciplinary approaches to solving energy challenges. Lastly, the bibliometric analysis, while providing a macroscopic view of the research domain, may overlook the qualitative aspects of the research contributions, such as the methodological robustness, theoretical frameworks employed, or the socio-economic contexts of the studies reviewed. This limitation underscores the need for future research to incorporate more qualitative analyses or meta-analyses that delve deeper into these aspects, providing a more rounded and comprehensive understanding of the field.

8. Future research directions

The future research directions in the application of blockchain technology within the renewable energy sector present a multifaceted landscape that extends beyond the technical and economic aspects to encompass socio-political, ethical, and environmental implications. This comprehensive approach is vital for ensuring that blockchain integration into energy systems aligns with broader sustainable development goals and addresses a range of challenges and opportunities.

One critical area for future research is the environmental impact of blockchain technology itself, particularly in the context of its energy consumption. While blockchain can enhance the efficiency of renewable energy systems, its significant energy footprint necessitates a careful assessment to ensure alignment with renewable energy goals. Investigating energy-efficient blockchain architectures, such as proof-of-stake or other consensus mechanisms, could provide a pathway for reducing the technology's environmental impact while maintaining its benefits. Another key direction is examining the socio-political and ethical dimensions of blockchain in renewable energy [202]. This includes exploring how blockchain-enabled decentralized energy systems can impact energy equity and accessibility [136]. As the sector moves towards more participatory energy models, such as P2P trading and prosumer frameworks, it becomes crucial to consider the readiness of existing infrastructures and the potential for exacerbating or mitigating energy inequalities.

Furthermore, the practical implementation of blockchain in real-world energy systems poses a significant challenge, bridging the gap between theoretical research and practical application. Future research must focus on overcoming regulatory hurdles, gaining market acceptance, and addressing technological limitations. This necessitates close collaboration between academia, industry, and policymakers to ensure that the advancements in blockchain technology are effectively translated into tangible benefits for the renewable energy sector. The thematic clusters identified through co-word analysis reveal additional specific areas for future research. For instance, the integration of blockchain with smart grids and EVs raises important considerations regarding privacy, security, and cybersecurity. Research in this domain must balance technological advancements with concerns about user privacy and the resilience of energy infrastructures against cyber threats.

Similarly, the application of blockchain in urban energy systems, as part of sustainable smart city initiatives, calls for inclusive and equitable approaches to ensure that these technologies are accessible to all segments of the population. The intersection of renewable energy, blockchain, and smart technologies also invites exploration into the infrastructural demands and complexities of implementing such integrated systems. Finally, the financial dimension of blockchain in the renewable energy sector, particularly its role in funding renewable energy projects and the use of cryptocurrencies, presents an intriguing area of study. This includes critically assessing the environmental impacts of cryptocurrencies and exploring alternative financing mechanisms for renewable energy initiatives.

Data availability statement

Data is available upon request.

CRediT authorship contribution statement

Abderahman Rejeb: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Karim Rejeb:** Visualization, Software, Resources, Data curation. **Imen Zrelli:** Supervision, Resources, Project administration, Funding acquisition. **Edit Süle:** Validation, Supervision, Project administration, Funding acquisition. **Mohammad Iranmanesh:** Writing – review & editing, Supervision, Software, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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