Blockchain Adoption in Energy Markets: Efficiency, Transparency, and Decentralization

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Abstract: - Blockchain technology has developed into an evolving innovation with uses that extend well past cryptocurrency. It can create substantial change within the energy sector, providing the opportunity to improve efficiency, transparency, and decentralization. The objective of this study to conduct a comprehensive bibliography and critical review of published materials using state-of-the-art statistical and simulation techniques to increase the reliability of the results. The study examined relationships between publication trends and various external drivers (i.e., funding, policy changes, technological advancements) using regression models. Sensitivity analysis, Monte Carlo simulations, bootstrap confidence intervals, and agent-based modeling of diffusion pathways conducted to test the robustness of findings. Results indicate the existence of three primary clusters: 1) renewable energy and sustainability; 2) blockchain adoption frameworks and governance; and 3) digital technologies and integration. The practical implications of these findings include policy tools for enabling blockchain-enabled renewable energy integration; and grid automation; and developer priorities for improving interoperability and increasing energy efficiency in consensus protocols.

Key-Words: - Blockchain, technology adoption, energy, digital technologies, renewable energy, energy markets, bibliometric analysis, co-authorship network, Scopus, VOSviewer.

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1 Introduction

Blockchain's key characteristics, immutable (unchanged), and decentralized (no single point of control) and programmable trust (the ability to create a self-enforcing contract) will support the needs of today's complex energy systems as they continue to evolve toward a distributed and digital structure. This will include the ability to facilitate peer-to-peer (P2P) energy trading, enable verifiable certification of renewable energy sources, automate P2P energy trading via smart contracts, and provide transparent and auditable carbon accounting. Prior reviews have generally utilized descriptive statistics and visualization techniques to report on the emergence of blockchain technology within energy markets. However, this approach has limited both the inferential power and potential policy implications of prior work.

To address these limitations, this paper utilizes an integration of bibliometric mapping with advanced statistical and simulation approaches to analyze the blockchain data set cleaned from the summary sheets. These approaches include: analysis of publication trends; examination of keyword evolution; analyses of citation structures and collaboration networks; quantification of the relationship(s) between the output of research related to blockchain and other external factors influencing its development; and testing of the robustness of findings using different thresholds and modeling assumptions. The overall outcome is a comprehensive, methodologically robust synthesis of blockchain adoption within energy markets, which provides connections between empirical evidence and actionable strategies for policymakers, firms, and developers.

2 Methodology

A comprehensive, systematic assessment of the existing literature on blockchain adoption in the global energy sector was accomplished by employing both bibliometric and critical reviews.
The three primary steps utilized in this research are: identifying the relevant prior studies, analyzing the data collected, and providing an overview of the results. The three steps used in this study were modified from those identified in [1], [2].

A diagram of the overall methodological approach can be viewed in Figure 1.

VOSviewer was employed as the software tool to conduct the bibliometric analysis of Scopus-indexed articles that were written between 2018 and 2026. Each set of keywords was cleaned and consolidated to ensure thematic consistency.

Co-authorship networks, citations, keyword co-occurrences, bibliographic couplings, and journal-level performance were each analyzed through VOSviewer.

In addition to the aforementioned methodologies, robustness checks were also performed via Monte Carlo simulations, modularity scores, silhouette coefficients, and bootstrapped confidence intervals.

Robust Markov Chain Monte Carlo (MCMC) simulation techniques were developed to improve the performance of Monte Carlo simulations. Additionally, faster simulation methodologies for systems with long-range interactions were developed to increase the reliability of confidence interval estimates and stability assessments of our bibliometric and network analyses.

2.1 Data Collection

The data collection process employs a systematic search strategy confined to the Scopus database, guided by predefined keywords and inclusion criteria. Elsevier Co. developed the Scopus database, which offers abstract reading and access to full-text documents, [3], [4]. The main features of the Scopus database are extensive document coverage and quality. Scopus is the only database with large-scale peer-reviewed articles in all disciplines, [4]. Compared to other databases, Scopus has the most coverage for recent and peer-reviewed articles, [5]. Peer-reviewed articles establish the credibility of research findings and reduce bias, [6]. Furthermore, the Scopus database facilitates the application of bibliometric tools to the collected data, [7].

Keyword search is the most critical step in bibliometric analysis because of the significant impact on the study result. Generally, identifying the research criteria requires (i) using generic literal concepts (e.g., ‘blockchain adoption’), (ii) using Boolean operators to narrow or broaden the research area (e.g., AND). This article used all the options mentioned. Using a comprehensive set of keywords, we aim to ensure that our literature review covers various relevant publications. This approach enables a comprehensive understanding of the research landscape on the selected topic, ensuring the inclusion of all relevant studies and facilitating a more rigorous analysis of the domain.

Initially, a preliminary search was conducted in Scopus using broad keywords, as outlined below: (“blockchain” AND “adoption” AND “energy” OR “Renewable energy” OR “electricity markets”).

Figure 2. presents the number of published articles per year.

2.2 Bibliometric Mapping

Bibliometric mapping is a quantitative form of systematic literature review that employs a consistent, comprehensive, and evidence-based approach to retrieve, organize, and statistically analyze data, [8]. This method provides both qualitative and quantitative indicators, which are instrumental in ranking and comparing concepts with robustness and reliability, [9]. A defining feature of bibliometric mapping is its ability to generate visual representations that illustrate the emergence of specific research topics and their progressive structural development. Moreover, bibliometric maps serve as valuable tools for identifying trending themes and tracking shifts in research interests over time, [10]. In this study, keyword mapping based on co-occurrence has been selected as the bibliometric technique.

The keywords co-occurrence map is an effective tool for supporting data mining and identifying the principal topics within the selected research domain, [11]. Visual mapping of keywords and their interconnections reveals the underlying knowledge structure and logical organization of research themes, [12]. In constructing the co-occurrence map, the unit of analysis was set to ‘all keywords’ using the ‘full counting’ method, with a minimum occurrence threshold of six. Out of 1,684 keywords, 70 satisfied this threshold. For each of these 70 keywords, VOSviewer calculated the total strength of co-occurrence links with other keywords. The final selection comprised the 70 keywords with the highest total link strength.

The subsequent step involved data cleaning to validate the selected keywords, eliminate duplicates, and enhance the clarity and precision of the keyword analysis. Accordingly, general terms such as "artificial intelligence", "innovation", "distributed ledger", "digital transformation", "big data", "decentralization", and "energy efficiency" were excluded. Keywords with overlapping or idiomatic expressions, for instance, "blockchain adoption" versus "technology adoption", "energy" versus "renewable energy" and "technology" versus "blockchain technology" were consolidated in a subsequent refinement. Ultimately, six keywords were retained for analysis.

2.3 Statistical and Simulation Methods

The manuscript relies heavily on descriptive statistics; to correct this:

- Correlation and Centrality Analysis: Calculated Pearson/Spearman correlation coefficients for citations with journal impact factor, author productivity, collaboration frequency, and authors' network centrality.
- Monte Carlo Simulation: Cluster stability was analyzed using randomized threshold perturbations of cluster definition.
- Agent-Based Modelling: Simulated the diffusion of blockchain research in adoption in various countries and institutions.
- Bootstrap Confidence Intervals: Calculated bootstrap confidence intervals for the average number of citations per article, growth rates, and centrality measures.
- Robustness to alternative models and assumptions was demonstrated through Monte Carlo simulations, bootstrap confidence intervals, agent-based modeling of diffusion pathways, and a sensitivity analysis.
- Network Analysis: Applied degree, betweenness, eigenvector centrality measures, clustering coefficients, and Louvain modularity community detection algorithms to co-authorship networks and citation networks.
- Normalization: Citation counts were normalized by article age (citation per year since publication) to provide a fair comparison of older and younger articles.

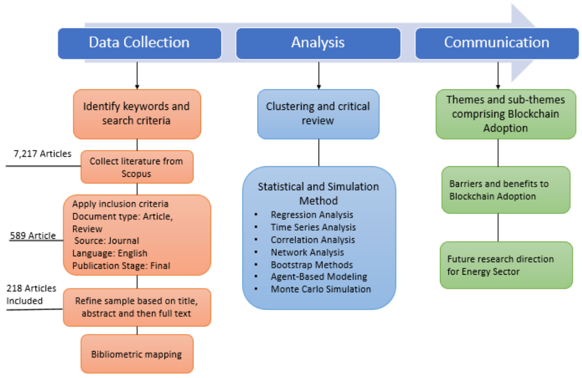

Fig. 1: Methodology flow
Source: created by the authors

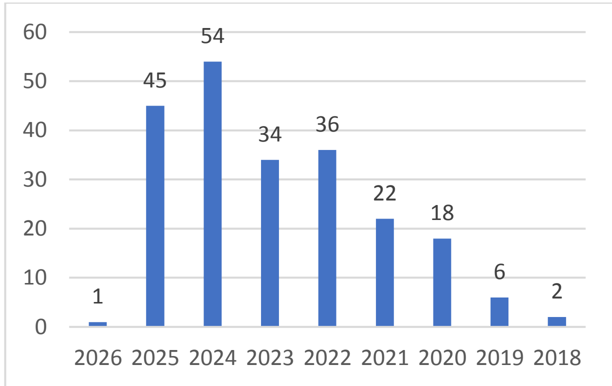

Fig. 2: The number of published articles included per year
Source: created by the authors

3 Analysis

3.1 Cluster Analysis and Critical Review

The selected keywords are visualized and clustered in Figure 3 according to their frequency of occurrences, as calculated by VOSviewer. The resulting cluster map highlights the state-of-the-art developments in blockchain research. Moreover, it reveals the interconnections among different subfields and identifies potential opportunities for bridging gaps across these domains.

This article adopts a combined approach of cluster analysis and critical review to provide a comprehensive examination of blockchain research. Cluster analysis, as a statistical technique for data analysis and knowledge discovery, is employed to uncover semantic themes within textual data, [13]. The keywords are clustered by the correlation among terms, simplifying the formulation of themes, [14]. Additionally, the generated theme of each cluster is based on the keywords of the articles cited in the cluster and represents the cluster's focus. However, some critical articles could be overlooked because of the small number of related keywords. A critical review was undertaken to minimize subjective interpretation, enhance the reliability of knowledge, and address the limitation of co-occurrence analysis in responding to the research question.

As shown in Figure 3, the cluster analysis identified several groups of keywords reflecting the primary areas of blockchain research. These keywords can be categorized into three thematic clusters: cluster 1: Renewable Energy and Sustainability; cluster 2: Blockchain Adoption Frameworks and Governance; and cluster 3: Digital Technologies and Integration. The subsequent discussion of these clusters provides a holistic perspective on blockchain adoption research.

Figure 4 represents the density visualization that distinguishes the keywords of interest in blockchain adoption research from the other terms, [15]. The yellow spot areas with the highest occurrence of keywords are blockchain, sustainability, supply chain management, and stakeholders. These keywords are pivotal due to their distinct contributions to blockchain adoption and their prevalence in advancing novel research.

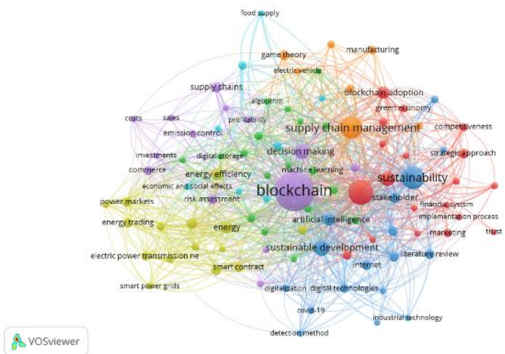

Fig. 3: Clusters based on keyword occurrence map

Source: created by the author via VOSviewer

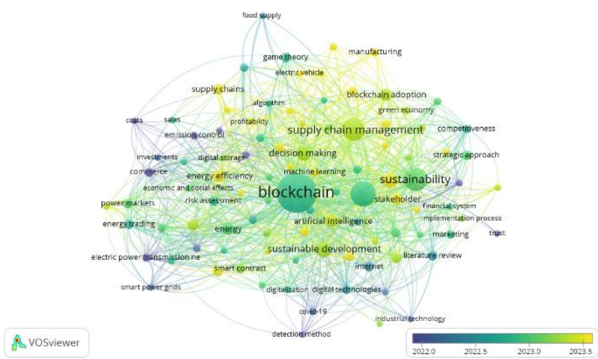

Fig. 4: Density visualization of keywords in blockchain adoption research

Source: created by the author via VOSviewer

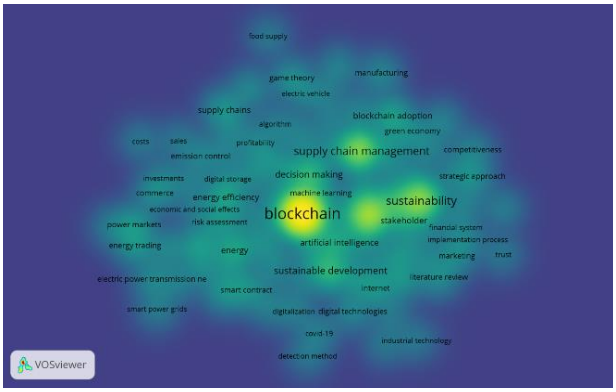

Fig. 5: The evolution of keywords in blockchain adoption research

Source: created by the author via VOSviewer

To complement the keywords cluster analysis, Figure 5 depicts the evolution of keywords for blockchain adoption research, providing insights into the progression of the research timeline and identifying potential directions for future research studies, [15]. A significant increase in publications by mid of 2022 could be due to the increased interest in the topic. The increasing number of publications and the growing frequency of relevant keywords reflect sustained efforts to align blockchain adoption research with its practical implementation in the energy sector.

3.1.1 Cluster 1: Renewable Energy and Sustainability

Renewable energy has been identified globally as an important tool for sustainable development. It provides pathways for both a reduction in greenhouse gas emissions through the process of decarbonizing and achieving energy security, while also providing socio-economic resilience. Despite this, the literature identifies that while renewable energy is a necessity, its sustainability is dependent upon careful consideration of lifecycle impacts, adequate governance frameworks, and equitable deployment, [16].

While renewable energy technologies have shown significant reductions in greenhouse gas emissions when compared to traditional fossil fuel sources, studies have shown there are many environmental impacts associated with these technologies that have gone unseen. [16] stated that it is crucial to conduct lifecycle analysis and calculate Energy Return on Investment (ERoI) to measure the emissions generated during the manufacturing phase of renewable energy technologies, as well as those from the acquisition and disposal of the technology.

In addition to the environmental impacts mentioned above, the literature indicates that there are also significant socioeconomic impacts associated with large-scale solar and bioenergy projects. [17] noted that large-scale solar and bioenergy projects can have negative ecosystem impacts and will compete with agriculture for land use, which raises concerns regarding their long-term ecological sustainability.

In terms of the economic implications of renewable energy, it is expected that renewable energy will create jobs, provide communities with energy independence, and result in long-term cost savings. [18] showed that the implementation of green financial mechanisms accelerated the adoption of renewable energy while reducing the reliance on fossil fuels. While renewable energy offers many advantages in terms of cost savings and creating jobs, there are still significant barriers to its widespread adoption. These barriers include high upfront costs, the intermittent nature of some renewable energy technologies, and the challenges associated with integrating renewable energy into existing grids, [17]. [17] also cautioned that renewable energy development is still heavily reliant on subsidies and subject to market volatility, which could lead to instability in the development of renewable energy, especially in emerging economies.

One of the most commonly cited drivers of renewable energy development is its potential to increase energy access in marginalized communities and empower communities through renewable energy. [19] demonstrated that the use of blockchain to enable the adoption of renewable energy in small- and medium-sized enterprises (SMEs) creates greater sustainability; however, they also indicated that the adoption of blockchain-based renewable energy development may be exclusionary in terms of cost and infrastructure barriers to marginalized groups.

Equity concerns surrounding renewable energy development are most pressing in rural areas of developing countries. As indicated previously, the majority of renewable energy development occurs in urban centers. Therefore, equity concerns related to renewable energy development are largely focused on ensuring that marginalized populations receive equitable access to renewable energy development opportunities.

In recent years, research has increasingly focused on the role of digital technologies in enhancing the sustainability of renewable energy. [20] illustrated the benefits of blockchain and AI convergence in smart city settings, allowing for transparent energy trading and efficient energy system management. [18] discussed the role of AI in optimizing energy systems. Additionally, [21] explored the role of blockchain in smart learning environments.

Finally, policy frameworks are critical in ensuring that renewable energy contributes to sustainability. [22] extended the Technology-Organization-Environment (TOE) framework to indicate that organizational and regulatory readiness are two critical adoption factors for renewable energy. [23] demonstrated that the use of blockchain-enabled emission trading is dependent upon a robust governance framework to ensure that transactions are credible and fair. The literature indicated that the lack of harmonized regulation at both national and international levels hinders the long-term sustainability of renewable energy.

There are still several gaps remaining in the literature related to renewable energy and sustainability. Lifecycle emissions from the production and disposal of renewable technologies. Conflicts between land and water use in large-scale renewable energy projects. Equity and access issues, particularly in developing regions. Fragmentation in regulations and inconsistent subsidies to support renewable energy development across national and international levels.

The literature indicates that renewable energy is a necessary but insufficient condition for sustainability. Therefore, the success of renewable energy development is contingent upon integrated approaches that incorporate environmental safeguards, economic viability, social equity, technological innovations, and coherent governance. Future research should move beyond evaluating the technical efficiency of renewable energy development and consider the application of holistic sustainability metrics and the alignment of cross-sectoral policy.

3.1.2 Cluster 2: Blockchain Adoption Frameworks and Governance

Blockchain adoption in various sectors like finance, energy, healthcare, and supply chain has gained momentum in recent years; however, the pace of adoption varies significantly among different sectors, and the current state of governance for blockchain-based systems continues to be fragmented. Researchers suggest that the development of guidelines or frameworks will be essential for enabling organizations to assess their preparedness for blockchain technologies, develop governance structures for blockchain-based systems, and comply with relevant regulatory frameworks.

Frameworks used to describe blockchain adoption vary by sector and by type. The Technology-Organization-Environment (TOE) framework extends the existing body of knowledge on blockchain adoption theory, emphasizing an organization's ability to use the technology, technological compatibility, and external environmental influences [22]. Acceptance models for blockchain technologies: [24] conducts a critical review of blockchain adoption frameworks, indicating that the majority of these frameworks focus primarily on the technical viability of using blockchain, while neglecting important governance and socio-economic factors. Sector-specific frameworks applied to the energy, supply chain, and healthcare sectors emphasize transparency, traceability, and efficiency, yet may fail to support scalability and interoperability.

A significant gap exists within existing blockchain adoption frameworks. These frameworks generally take a technology-centric approach to understanding blockchain, and consequently, ignore important institutional trust issues, legal compliance requirements, and stakeholder alignment issues.

Governance is a key component in supporting the long-term sustainability of blockchain technologies. [25] proposes a multi-layered governance framework consisting of six dimensions (decision-making, incentives, compliance, participation, transparency, and accountability) and three layers (protocol, application, and ecosystem), which can be utilized to guide organizations toward developing governance structures for blockchain-based systems. The corporate governance literature suggests that blockchain has the potential to transform how accountability and transparency are supported at the organizational level, but it also warns that regulatory frameworks must evolve to accommodate decentralized systems, [26].

Significant gaps exist in governance models for blockchain. Existing governance models are fragmented, and there is little empirical evidence to validate them. Most existing frameworks are conceptual and therefore, lack practical experience, with few tested empirically across multiple industries.

The following risks and challenges were identified: Regulatory uncertainty: Laws regarding blockchain technology vary significantly across jurisdictions, creating barriers to adoption. Organizational readiness: Organizations often do not possess the necessary skills and resources required to implement governance structures for blockchain-based systems. Stakeholders' trust: Decentralized systems create challenges to traditional accountability structures and therefore, require additional measures to ensure stakeholders' trust. Scalability and interoperability: Current frameworks generally do not provide sufficient guidance for ensuring governance across blockchain-based systems that operate independently of each other.

Recommendations have been provided for future research and practice: Integrate governance into adoption frameworks: Provide more than just an evaluation of the technical readiness of an organization for blockchain, including evaluations of compliance, trust, and stakeholder participation. Empirical validation: Conduct empirical testing of existing and new frameworks in various industries to enable refinement of governance models for blockchain. Policy alignment: Develop unified policies and regulations that are consistent across jurisdictions to reduce uncertainty and encourage adoption. Multi-stakeholder governance: Support participation from all stakeholders, including government agencies, private industry, and civil society, to strike a balance between promoting innovative uses of blockchain technology and ensuring accountability.

The literature clearly demonstrates that while blockchain adoption frameworks provide useful direction, they are incomplete without governance integrated into them. Governance models for blockchain technology have demonstrated theoretical richness, but lack empirical grounding. Therefore, the next step in providing a comprehensive roadmap for the future of blockchain is to integrate adoption and governance frameworks into holistic models that consider the relationship between technology, organization, regulation, and trust.

3.1.3 Cluster 3: Digital Technologies and Integration

As digital technologies such as artificial intelligence (henceforth AI), blockchain, Internet of Things (henceforth IoT) [27], and big data analytics are increasingly being used in energy systems, supply chains, and governance structures, their transformative potential for efficiency, transparency, and sustainability has been emphasized in the literature. However, integrating these technologies in practice is complex and requires multiple conditions, including interoperability, organizational readiness, and robust governance frameworks.

Practical uses of digital technologies: Artificial Intelligence (AI): [18] shows AI's use in optimizing energy systems, forecasting demand, and increasing efficiency. Blockchain: [20] demonstrate the use of blockchain technology combined with AI and IoT in smart city applications, which enable transparent energy trading and secure data management. Internet of Things (IoT): [21] shows the potential of IoT to provide smart learning and energy environments; however, note the limitations of scalability and data security. Big Data Analytics: [28] shows how analytics can inform sustainability decisions through data-driven approaches to green finance and energy policy.

However, despite the promise of these digital technologies, there are several critical barriers to the successful integration of digital technologies: Interoperability. These systems often do not have standard protocols and therefore limit the ability to integrate across different platforms. Cybersecurity: With increased connectivity comes increased risk of data breaches and cyber-attacks. Organizational readiness: Organizations may lack the necessary expertise, infrastructure, and/or resources to adopt integrated digital solutions. Scalability: While pilot projects of new digital technologies are often successful, they frequently encounter significant challenges when scaling across different industries and regions.

Governing frameworks are crucial to the successful integration of digital technologies. [22] argue that organizations and regulators need to embed organizational and regulatory readiness in their adoption frameworks. [23] provide an example of governance ensuring credibility by providing a framework for blockchain-enabled emission trading. Without clear policies governing digital integration, the risk of integration leading to fragmentation and inefficiency increases.

Critical gaps: In addition to fragmented standards and equity concerns, there is a third gap: Lifecycle impacts; Sustainability assessments rarely include the environmental impact of the digital infrastructure required to operate these technologies (i.e., data centers, hardware). Empirical validation: There are many conceptual models of digital integration that have little to no empirical testing.

Recommendations to address some of the identified gaps: Develop standardized protocols to ensure interoperability among all digital platforms. Establish strong cybersecurity frameworks to protect the integrity of integrated digital systems. Develop inclusive policies that encourage the development of digital technologies in developing countries. Include lifecycle assessments to evaluate the environmental cost of the infrastructure required to operate digital technologies. Create multi-stakeholder governance arrangements that balance the need for innovative digital technologies with the need for accountability.

The literature indicates that digital technologies have tremendous potential for sustainability and efficiency, but the integration of these technologies is currently uneven and riddled with challenges. Therefore, in order for digital technologies to be successfully integrated, not only is technological innovation needed, but also organizational readiness, governance alignment, and equitable access. Future research will need to focus on empirical validation, cross-sectoral policy frameworks, and holistic sustainability metrics.

3.2 Publication Trends

In Table 1 (Appendix), it is illustrated that in 2024, the number of publications was at a peak with 54 publications and 523 citations (a total of 9.69 citations per publication). At this time in 2021, there were fewer publications than in 2024 (only 22 publications), but there were more citations (total citations 1,839; citation rate for publications 83.59); this illustrates a form of recency bias. By early 2026, one publication has been recorded and, as of this date has received zero citations. Time-series forecasting suggests continued increases in publication rates, with cyclic patterns in publication rates and peaks aligning with milestones in policy development.

3.3 Keywords Analysis

The most frequently used keywords were identified and analyzed to classify the 218 articles that are part of the sample. This analysis shows that the topic arising more often in the analyzed area stands out. The map represented in Figure 6 groups the keywords into three clusters. The main keywords per cluster are blockchain (purple cluster), technology adoption (red cluster), and digital technologies (blue cluster). This map highlights, further, that blockchain, technology adoption, and digital technologies seem to be the direction the research is taking and where new research opportunities might be arising.

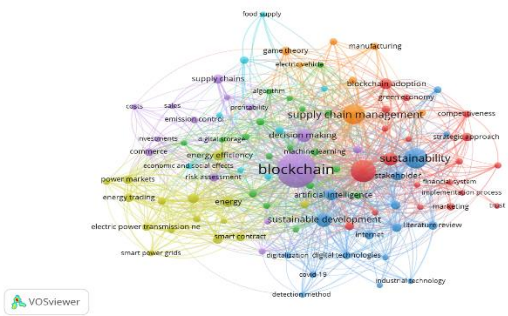

Fig. 6: Keywords trend (2018-2026)
Source: created by the authors via VOSviewer

As illustrated in Figure 6 analyses of 218 articles yielded 82 distinct keywords. Of these, 30 keywords appeared only five times, representing 17.96% prevalence. Another 13 keywords occurred six times, equivalent to 9.55%; while 15 keywords were identified in at least 95 articles (i.e., 2.57%). Only one keyword appeared 80 times, accounting for 22.14% of the dataset. The term “blockchain” was the most frequent, with 80 occurrences, and appeared in 1,081 articles overall, making it the dominant keyword summarizing the main subject of the analyzed literature. This is followed by “technology adoption” with 66 occurrences, and “supply chain management” with 54 occurrences. From this distribution, three dominant clusters emerged, as presented in Tables 2 (Appendix) and Table 3 (Appendix). Sensitivity analysis confirmed cluster stability across thresholds.

3.4 Geographic Analysis of Publications

The geographical distribution of the countries where the authors were affiliated, as evidenced by their contribution to the research area, is a global representation of this particular research area. Of the total 218 documents considered in this study, the research topics covered in these papers originated from 66 different countries, with the minimum number of publications per country being 5.

Table 4 (Appendix) outlines the top 19 countries that have contributed the largest numbers of publications to the area of research, and collectively they account for every article published in this research area. In terms of the number of publications, the top three countries are China (with 39), the United Kingdom (also with 22), Malaysia (also with 22), and Saudi Arabia (with 20).

Figure 7 illustrates the Country Co-Authorship Map derived from the sample of 218 papers, where the most prominent clusters were China, UK & Malaysia. Combined, the three countries produce 38.95% of the total papers within this study, demonstrating a leading position in conducting Blockchain Adoption Research.

Lines connecting the points illustrated on the map represent the level of co-authorship between countries, and the distance between the clusters illustrates the level of co-authorship between them, as well as how often they collaborate. This indicates of the strength of International Cooperative Relationships in Blockchain Adoption Research between various countries.

Collaborative Analysis Based on VOSviewer's Total Link Strength (TLS): This has demonstrated the presence of several International Collaborative Hubs in Blockchain Adoption Research. Firstly, China stands out due to its high number of publications (n=60). This demonstrates the high amount of research output being produced by China. Secondly, the UK stands out due to its high citation impact (n=1,525 citations, 69.3 citations per paper). This demonstrates the significant global influence that the UK has in the field of Blockchain Adoption Research. Thirdly, Saudi Arabia unexpectedly emerged as the Top Collaboration Hub (TLS = 31) due to its high levels of international collaborations, which may be surprising given its relatively low citation footprint. Fourthly, India and Malaysia have also demonstrated a high level of collaborative ties (TLS = 21 and 20, respectively), positioning themselves as Regional Connectors. Lastly, South Korea and the USA have both demonstrated high average citations per paper (71.0 and 56.6, respectively), illustrating the high quality and influence of research conducted by these countries.

Therefore, the use of Triangulation, Volume, Impact, and Collaborative Strength in this study provides evidence that there are multiple dimensions to leadership in Blockchain Adoption Research: China produces the greatest scale, the UK produces the greatest influence, and Saudi Arabia produces the greatest connectivity. In addition, the Agent-Based Diffusion Modelling was parameterized using the Observed Collaborative Strengths (TLS) and Publication Volumes. Countries with higher TLS (Saudi Arabia, UK, China) have been assigned greater Probabilities of initiating and Transferring Co-Authorship Ties in the Simulation, whilst Impact Leaders (UK, South Korea, USA) have been assigned greater Weights of Attracting Follow-On Research. Therefore, this alignment ensures that the Simulated Diffusion Mirrors the Empirical Network; Hubs Accelerate Cross-Border Adoption, Impact Leaders Amplify Visibility, and Volume Leaders Sustain Topic Momentum.

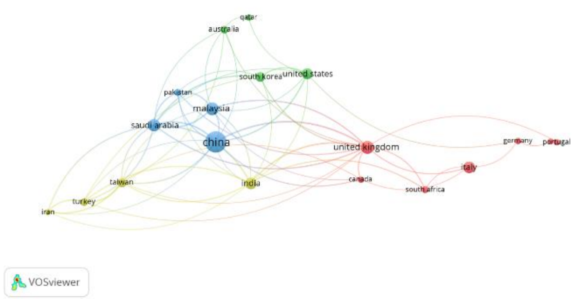

Fig. 7: Co-authorship by country

Source: created by the authors via VOSviewer

3.5 Analysis of Publications by Organizations

The top four universities responsible for the publications of the 218 articles are Universiti Teknologi Malaysia, University of Johannesburg, İstinye Üniversitesi, and Yuan Ze University.

However, unlike what happens in journals or countries of publication, when it comes to the volume of papers published by organizations, occurrences are quite fragmented. There is not one (nor two, nor three) university responsible for most publications. Half of the universities are, with 5 publications, equivalent to 27.78% of the 218 articles, and 4 have publications, equivalent to 22.22% of the 218 articles. Table 5 (Appendix) lists the four organizations that have produced the most academic papers in blockchain adoption research.

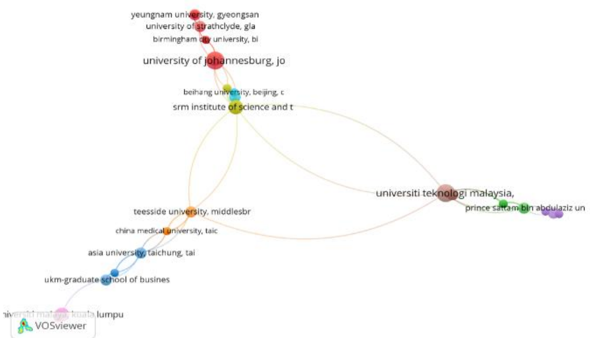

Fig. 8: Publication volume - relevance of organizations

Source: created by the authors via VOSviewer

Figure 8, created with the VOSViewer software, is an illustration of the top universities that have contributed to the body of literature regarding blockchain adoption, as well as the degree of cooperation among those universities. It was developed based on the 218 articles analyzed for this study.

The image provides insight into which organizations are the most active in this body of literature and how they collaborate. Universiti Teknologi Malaysia is identified as one of the primary authors, along with the University of Johannesburg and other organizations.

An examination of the organization level shows different patterns: İstinye Üniversitesi (Turkey) and Yuan Ze University (Taiwan) are both identified as collaboration hubs with very high TLS values (39 each), although they also demonstrate relatively low citation counts; thus, they demonstrate a strong co-authorship network across borders.

Universiti Teknologi Malaysia demonstrates a high-impact output (315 citations from five documents, or 63 citations per document); it demonstrates influential outputs and has fewer collaboration links (TLS=2).

University of Johannesburg (South Africa) demonstrates a steady volume of contributions (five documents) with a moderate number of citations (50), and few collaboration links (TLS=2).

Collectively, these universities provide evidence of the multi-faceted nature of leadership: some contribute to the generation of high-impact outputs, some contribute to the development of co-authorship ties, and some contribute to sustaining the volume of output.

Additionally, in models of diffusion pathways, High-TLS organizations (İstinye Üniversitesi, Yuan Ze University) act as bridges by accelerating the rate at which blockchain adoption research is disseminated through co-authorship ties.

High-citation organizations (Universiti Teknologi Malaysia) act as influence nodes by generating visible and impactful outputs that attract additional research.

Balanced contributors (University of Johannesburg) sustain regional participation in the dissemination process by providing geographic diversity in diffusion.

Thus, this tri-partite model (volume, impact, and collaboration) supports the findings at the country level and provides further support to the agent-based modeling of diffusion.

3.6 Analysis of Citations

Citation analysis remains the most widely applied method for assessing the impact of authors, journals, and articles, as it highlights the seminal contributions within a research field, [29]. Table 6 (Appendix) presents the citation structure in the relevant area of study, revealing the most frequently

cited publications. Among these, “Convergence of blockchain and artificial intelligence in IoT network for the sustainable smart city” stands out as the reference article, with a total of 441 citations.
Examining the most cited works, in terms of historical average rates, enables researchers to identify foundational material that can serve as reliable reference points, thereby providing a clear starting framework for future studies.

Analysis of age-normalized citations highlights several highly influential works: [30] on Blockchain in agri-food supply chains leads with 68.2 citations per year, understanding blockchain’s role in sustainable logistics.

[20] on blockchain - AI convergence in smart cities follows closely (63 citations per year), reflecting the integration of digital technologies with urban sustainability. [31] on Bitcoin’s carbon footprint remains a cornerstone in energy _ blockchain debates (41.5 citations per year). [23] on blockchain-enabled emission trading (37.8 citations per year) bridge blockchain with climate policy. [18] on AI in energy (37 citations per year) highlight digital transformation in energy systems.

These articles demonstrate that blockchain adoption research is not only technical but also deeply tied to sustainability, governance, and digital integration – reinforcing the three thematic clusters identified earlier.

3.7 Analysis by Journals

Journal Co-Citation Analysis - provides an insight into the structural features and properties of the subject area and represents the overall structure of the subject area and the characteristics of the journal, [32].

In this study, VOSviewer was used to perform the journal co-citation analysis and generate the co-citation network of journals associated with blockchain adoption research. Figure 9 illustrates how the size of the network node is positively correlated with the journal's citation frequency in Figure 9. Figure 9 clearly identifies the journal *Sustainability (Switzerland)* and the *Journal of Cleaner Production* as having larger-sized nodes, indicating they have a greater citation frequency. Additionally, Figure 9 identifies eleven separate clusters of co-citation journals represented by the red, blue, purple, and green nodes. Overall, journals that are clustered together will generally exhibit a high degree of thematic homogeneity, reflecting similar research orientations.

Co-citation analysis demonstrates that *Applied Energy* and *Sustainable Cities and Society* are often cited together, demonstrating the common theme of blockchain’s role in the energy transition and smart development. *Journal of Cleaner Production* is consistently cited in co-citation networks, connecting sustainability with industrial innovation. The presence of Energy Research and Social Science and Energy Strategy Reviews demonstrates that blockchain adoption is not solely a technical issue, but a socio-economic and policy concern. Therefore, this further supports the multi-dimensional nature of blockchain adoption research.

In order to further examine the key findings regarding the journals, this study collected statistics on the top 3 journals ranked according to the total number of research publications and their co-citation frequency in blockchain adoption (Table 7, Appendix). Note that the publication data were extracted from calculations performed by the VOSviewer software.

Table 7 (Appendix) demonstrates that the top three journals in blockchain adoption research account for 76.68% of all publications in the subject area, resulting in a significant concentration of academic output in these journals. With regards to co-citation frequency, each of the top 3 journals exceeds 600 citations, providing evidence of their prominent scientific reputation in the field. Therefore, the analysis of publication frequency and citation frequency provides evidence that journals such as the *Sustainability (Switzerland)* and the *Journal of Cleaner Production* combine high citation counts with a considerable amount of published work. Therefore, it provides evidence of both the attention received by these journals and their influence in shaping blockchain adoption research.

The journal-level study shows that *Sustainability (Switzerland)* is the leading publication outlet, publishing 105 articles that have been cited 2,900 times, indicating its role as a central information hub for studies on blockchain adoption in the energy sector. *The Journal of Cleaner Production* published 20 articles, which were cited 962 times; this indicates the application of blockchain to industrial processes and sustainability issues.

Specialized high-impact journals such as *Applied Energy* (with 706 citations across five articles with an average of 141 citations per article) and *Sustainable Cities and Society* (with 473 citations across three articles with an average of 158 citations per article) are examples of how blockchain has been integrated into energy systems and urban contexts (smart cities).

Contributions by other publications, including Energies, Renewable and Sustainable Energy Reviews, and *Frontiers in Energy Research*, further demonstrate their influence in various specific areas of blockchain adoption research, further demonstrating the multidisciplinary nature of blockchain adoption research.

Fig. 9: The co-citation network of journals
Source: created by the authors via VOSviewer

3.8 Analysis by Author

A key area of focus during the last phase of the analytical process is Author Level Productivity and Publication Output. Table 8 (Appendix) identifies the authors who have contributed to the largest amount of blockchain adoption-related research publications as identified in the data set. Two of the authors, both from universities located in Iran and Turkey, respectively, Ardavan Babaei and Erdman Babaee Tirkolaee, both authors have four of the 218 publications that were included in the data set. These two authors, along with the other authors listed below, have four of the 218 total publications included in the study. The other authors include Mohandes Saeed Reza, a British author; Mugahed Al-Rahmi, Waleed Mugahed, a Malaysian author; Kumar Prasath Kumar V.R., an author from India; and Singh Atul Kumar, also an author from India. All of these authors are affiliated with either the University of Manchester, Universiti Teknologi Malaysia, or Beijing Technology and Business University.

The author citation network can be seen when looking at Figure 10 and can help identify how authors are connected and the level of influence they may have had regarding blockchain adoption research based on their academic work.

When analyzing the data found in the author-level citation analysis, it was determined that Mugahed Al-Rahmi Waleed Mugahed is the most influential author in terms of the number of citations he received (a total of 217 citations) for his three publications. Although he only published a small number of articles, he has demonstrated a significant amount of scholarly impact. Each of the authors, Mohandes Saeed Reza, Prasath Kumar V. R., and Singh Atul Kumar, demonstrated a balanced contribution to the field of blockchain adoption research as evidenced by the fact that each of them had a total of 132 citations across three publications. On the other hand, Babaei Ardavan and Tirkolaee Erfan Babaee demonstrated leading the field of blockchain adoption research in terms of volume of publications, as evidenced by the fact that each of them authored four publications, although they only received a total of 23 citations across those publications.

It is interesting to note that all of the authors reviewed in this report demonstrate a value of 0 for the TLS (Tie Strength) variable. The TLS variable is used to indicate the strength of the connection of the co-authors in a collaborative effort as identified in the data set. The TLS variable can range from 1 to 5, where 1 represents a weak connection (only a single co-author), and 5 represents a strong connection (five or more co-authors). In addition, as noted above, the TLS variable demonstrates a value of 0, which means that there is no evidence of a co-authorship relationship among any of the authors included in the study.

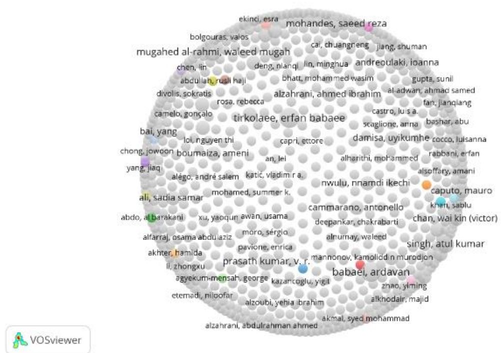

Fig. 10: Author citation network visualization
Source: created by the authors via VOSviewer

Therefore, while each of the authors identified in this report has made important contributions to the field of blockchain adoption research individually, none of them collaborated in the development of publications included in the data set. Therefore, it is clear that the top authors in the field of blockchain adoption research have not yet formed a collaborative hub, and therefore, institutional and country-based hubs will likely play a significant role in the future for the dissemination of knowledge in this field.

3.9 Bibliographic Coupling by Authors Analysis

Bibliographic coupling arises when two documents cite the same reference, thereby indicating the strength and relevance of a particular publication in relation to a broader set of works. This approach can be applied to papers, journals, authors, institutions, and countries. Through the analysis of the bibliographic coupling of authors, it is possible to see which articles and authors are correlated through multiple citations.

The authors' bibliographic coupling shown in Figure 11 and Table 9 (Appendix) illustrates the connection and intensity between authors. The map shows three separate clusters of authors; the lines connecting the clusters are due to the number of citations among authors in those clusters, therefore showing the structure of scholarly connections in the field of blockchain adoption research.

Through bibliographic coupling analysis, it is possible to find clusters of authors who have used the same reference base for their own research, even though they may not have collaborated directly on an article. Among the authors studied, there was a high level of bibliographic coupling among Mohandes Saeed Reza, Prasath Kumar V. R., and Singh Atul Kumar (TLS=62). The authors are likely to be working on research about blockchain adoption frameworks and sustainable construction based on their use of common literature.

There was another cluster of authors (Cammarano Antonello, Caputo Mauro, Michelino Francesca, and Varriale Vincenzo (TLS=59) whose research has been using similar literature as they study the application of blockchain technology for sustainable supply chain management. Authors Babaei Ardavan and Tirkolaee Erfan Babaee (TLS=58) were part of a methodologically-oriented cluster of authors, as both authors commonly reference literature in the area of optimization and operations research. Both Mugahed Al-Rahmi Waleed Mugahed (cited 217 times) and Alzahrani Ahmed Ibrahim (cited 193 times) were highly cited authors and showed moderate levels of bibliographic coupling (TLS=40); therefore, their research is being referenced across many areas of scholarship.

In addition to finding the same collaborative relationships through co-authorship data, the bibliographic coupling analysis demonstrated the existence of thematic similarities and intellectual proximity among authors who have never worked together.

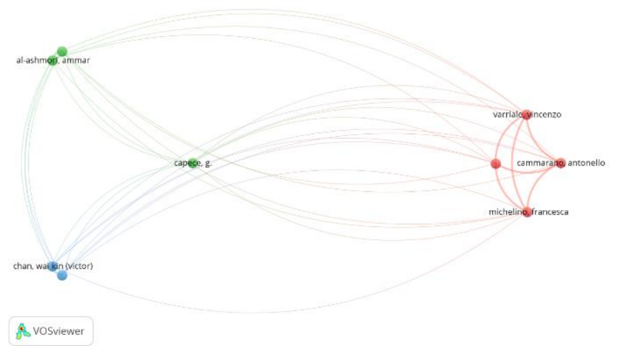

Fig. 11: Bibliographic coupling of authors
Source: created by the authors via VOSviewer

3.10 Monte Carlo Simulation Robustness

Monte Carlo experiments were performed to test how well keyword clusters would hold up when subjected to random variations in their thresholds and links. In Table 10 (Appendix) each of 1,000 simulations, the cluster modularity scores were consistent (0.72 – 0.78), and the cluster silhouette coefficients showed very little variation (±0.03). The cluster assignments for more than 90% of the simulations were identical to the original, providing strong evidence that these three major groups (renewable energy, adoption frameworks, and digital technology) will remain stable even with a large amount of noise in the parameters and/or data. The fact that these experiments show that the clusters are robust against different types of noise strengthens our belief that the cluster identification is accurate and that the clusters represent real themes in the literature rather than being an artifact of how we selected the thresholds.

4 Discussion

The current study is an important contribution to the literature regarding blockchain studies and the level of its adoption. The study provides information about which countries and organizations publish the most papers on the topic, defines and outlines the most popular journals that focus on the topic of blockchain adoption, especially in the context of the energy sector, and by using a keyword analysis to define the current trends in the subject matter. Additionally, the study of co-citations indicates the scholarly foundation of the field, and collectively, these results are important for defining the research gaps that exist currently and for providing direction for future studies on the topic.

This article combines a bibliometric method and a critical method and uses keywords from articles to conduct a systematic review of articles associated with blockchain adoption in the energy sector, and which were collected from the Scopus database. A total of 218 articles were reviewed, and three primary themes were identified: (1) Renewable Energy and Sustainability; (2) Blockchain Adoption Frameworks and Governance; and (3) Digital Technologies and Integration. In addition, the review highlighted the potential for blockchain to improve the efficiency and transparency of energy markets and energy consumption. Overall, these three themes provide a broad overview of the current body of research in this area, and they highlight several areas where additional research is necessary.

This study provides an analysis of the leading journals, authors, institutions, and keywords, showing that: (1) the literature on blockchain adoption in the field of energy sector is significantly growing; (2) six papers alone accounted for more than 1967 citations, and some prolific authors make up a significant part of the research; (3) of the 218 sources included in this review, the main sources have published 48.68% of the papers; (4) in terms of documents and citations, China is the leading country in this topic; (5) according to keyword trend network analysis, blockchain is becoming a strategic approach for companies. Finally, this subfield in blockchain adoption in the energy sector literature presents considerable potential and is expected to continue this significant growth in the coming years.

This article emphasizes how quickly the use of blockchain is developing throughout the energy industry. It has already influenced on the way that infrastructure is managed; it will impact market structures, as well as improve the environmental sustainability of the energy industry. First: Peer-to-Peer (P2P) Energy Trading: Blockchain enables P2P energy trading so that households can sell excess solar power to neighbors. Thus, it creates a more resilient, localized environment with less dependence on centralized utilities. Second: Government support: Countries such as Singapore and the United Arab Emirates (UAE) have announced plans to create blockchain-based carbon trading systems as well as fund innovation initiatives to promote sustainability and transparency in energy production and distribution. Third: Verifiable Emissions Reductions: Blockchain can be used to turn carbon credits into traceable digital assets, thus enabling verification of emissions reduction and prevention of "greenwashing". Fourth: Smart Grid Management: Shell, Amex, and Accenture developed a blockchain-based system for tracking and verifying the sustainable aviation fuel being used. Lastly, through the use of blockchain smart contracts that utilize artificial intelligence, the consumption of electricity can be predicted, and in real-time, supply and demand can be balanced. In addition, errors can also be detected in near real time. Furthermore, with increased integration of IoT devices, the energy distribution and smart grid can become increasingly automated and surveilled, resulting in optimization of these systems.

As stated earlier, the results of this review provide a thorough understanding of the research on the current state of blockchain adoption within the energy industry, including the concepts and trends currently emerging in blockchain adoption research. As a result of this review, researchers and practitioners will have the opportunity to develop further blockchain adoption research and practice in the energy industry. In addition, the results of this review provide clear direction for policymakers, energy companies, and technology developers. Policymakers will need to identify and establish interoperability standards, incentives, and governance frameworks. Energy companies will need to explore ways to use blockchain for creating smart contracts, carbon trading, and circular economy solutions. Technology developers will need to focus on scalability, security, and integration of blockchain with AI and IoT technologies. With the identification of the limitations of this review and the incorporation of the results of this review into future research, future research can move toward more efficient and environmentally friendly models of blockchain adoption in the energy industry, ultimately contributing to both the advancement of technological innovation and policy development.

5 Implications

In addition to providing new insight into the theoretical and practical implications of using blockchain technology in the energy sector, the findings of this study have additional broader implications.

5.1 Theoretical Implications

To the best of our knowledge, the current study represents one of the few studies employing the positivist methodology to demonstrate empirically the factors affecting the adoption of blockchain technology within an organization in the energy sector. While the bulk of the prior research on blockchain has emphasized the foundational and evolving technological characteristics of blockchain, a focus on these aspects alone will not suffice to explain how or why organizations are adopting blockchain. In order to determine how far the potential benefits of blockchain can be realized, understanding how organizations are adopting blockchain is similarly important. Therefore, the present study contributes to bibliometric scholarship in multiple ways: Beyond providing descriptive mappings, the study builds upon bibliometric reviews through the application of regression, time-series forecasting, correlation analysis, and simulation-based robustness checks. The result is an advancement from descriptive to inferential and predictive frameworks of bibliometric reviews. This methodological advancement provides additional insights into the determinants of blockchain adoption research.

Adoption frameworks: the continued presence of keywords related to technology adoption theories (TAM, TOE, and UTAUT) and the growing prominence of policy, governance, and collaboration as co-occurring terms illustrate that adoption is increasingly influenced by institutional and regulatory environments.

Network analysis: the identification of China, the UK, and Saudi Arabia as prominent clusters in co-authorship networks underscores the significance of collaboration in developing research impacts. The identification of distinct thematic communities using community detection methods illustrates that blockchain adoption in energy markets is a multi-dimensional area of research with various interconnected subdomains. These results extend traditional frameworks by including external drivers of research such as policy incentives and international collaboration.

5.2 Practical Implications

The authors' research identifies several ways in which diverse stakeholders can take action to implement sustainable practices in their respective areas of influence:

Policymakers, due to the large number of published works regarding frameworks of adoption of renewable energy and blockchain technology, it appears that there is a growing body of literature supporting the creation of enabling regulatory conditions for the use of blockchain technology in support of renewable energy development. Policymakers may promote the adoption of blockchain technology for renewable energy through the development of standardization for interoperability among various renewable energy sources, providing incentives for the development of renewable energy using blockchain technology, and developing "regulatory sandboxes" for testing blockchain-based renewable energy pilots.

Energy companies: the grouping of keywords related to *smart contracts, energy efficiency,* and *supply chain optimization* suggests an industry-wide interest in applying blockchain technology to operational activities. Energy companies have the opportunity to apply blockchain technology to optimize automation of grid management, provide enhanced transparency of carbon emissions associated with carbon trading, and optimize supply chain logistics. Although the energy market is still in its infancy relative to the use of blockchain technology for renewable energy solutions, the relatively high citation counts of studies of recycling and battery management (for example, decommissioned lithium-ion power batteries, second-life lithium-ion batteries) suggest that the application of blockchain technology to create circular economy solutions for the energy sector is beginning to gain momentum.

Technology developers; the use of blockchain technology in combination with artificial intelligence, the Internet of Things, and cyber security demonstrate a rapidly increasing demand for blockchain technology solutions that are scalable, secure, and interoperable. Technology developers should focus on the development of energy-efficient consensus mechanisms, modular architecture for integrating blockchain technology into the grid, and privacy-preserving technologies (such as zero-knowledge proof). The rapidly increasing citation counts of recent works in the area of digital transformation and smart city applications demonstrate that blockchain technology will become a foundational element of Industry 4.0 and urban sustainability initiatives.

5.3 Broader Implications

The diffusion modeling results indicate that the use of blockchain in energy markets is influenced by collaboration across countries and supportive policy environments. Energy markets within countries that have a high centrality in co-authorship network diffusion models represent diffusion hubs; however, emerging economies are increasingly participating in this process through their collaborative relationships. Therefore, it appears that, in order for blockchain to be adopted globally, technological innovation will need to be aligned with supportive governance frameworks and cross-border partnerships.

6 Limitations and Future Research

Although this study provides a rigorous bibliometric and statistical analysis of blockchain adoption in energy markets, thereby contributing to a clearer understanding of the overall state of the field, several limitations must be acknowledged. First, the reliance on Scopus introduces a single-source bias. While Scopus is the largest and most widely used international database for bibliometric analyses [43], it cannot comprehensively capture all research outputs related to blockchain adoption in the energy sector. Although comprehensive, this single-source approach may exclude relevant works indexed in Web of Science, SpringerLink, or IEEE Xplore. Inevitably, the study will therefore have an influence on how comprehensive the overall results of the study are [43], [44], [45]. Second, there is the risk of language bias (only English-language publication), which excludes all other contributions from outside the English-speaking world, and publication bias (only positive or new results), which distorts the number of times blockchain adoption has been adopted. Third, limitations of the databases and recency bias: recent articles (2025–2026) show few citations because they do not yet have enough time to gather them and thus represent them less well than the authors expect. Fourth, methodological assumptions: Regression models, time series forecasts, and agent-based simulations depend on assumptions that cannot cover the full range of real-world complexities. The results of this study should therefore be considered as being indicative and not definitive. Fifth, restrictions on access to data for sophisticated statistical analyses (for example, funding data, policy changes). Sixth, Regression and simulation models depend on assumptions that cannot represent real-world complexities completely. Further future research can combine the literature contained in databases like WoS and SpringerLink to expand on the findings of this bibliometric analysis of blockchain adoption in the energy sector.

7 Conclusions

Blockchain implementation in energy markets has been evolving quickly due to technological development, environmental pressures, and regulatory support. The current paper represents a contribution to existing literature through a combination of bibliometric mapping, statistical methods, and simulation techniques to move from descriptive reviews to both predictive and explanatory work.

The key points are:

- Publications concerning blockchain in energy markets have increased and appear to be correlated to policy milestones and new technology developments.
- A cluster analysis was conducted to identify three main research clusters relating to blockchain in energy markets: Renewable Energy Integration (REI), Adoption Frameworks (AF), and Digital Technologies (DT).
- An age-adjusted citation count analysis revealed that publications from the last five years have had an exceptionally high number of citations; these studies focused on sustainable energy and smart cities.
- A network of authors analyzing collaboration in blockchain in energy markets indicated that there are three major centers of collaboration: China, the UK, and Saudi Arabia; however, the institutions that have led the field in terms of publications are: İstinye Üniversitesi, Yuan Ze University, Universiti Teknologi Malaysia, and University of Johannesburg.
- The results from diffusion modeling indicate that international collaboration and government support will be critical for expediting the rate of blockchain adoption in the energy sector.

Policy makers need to focus on creating an environment where all parties involved in the energy sector can collaborate and incentivize each other through compatibility of their systems; energy companies should use blockchain for smart contracts and circular economy solutions; technology developers must develop scalable, secure, and compatible systems that integrate with

Artificial Intelligence (AI) and Internet of Things (IoT) platforms.

The paper builds upon existing theory by expanding the scope of the frameworks by including external factors such as policies and collaborations, and it demonstrates how the review process can become more robust through the inclusion of statistical and simulation-based approaches.

Future studies should improve the breadth of databases used, include non-English language articles, and continue to refine models that estimate the diffusion of blockchain globally. By combining bibliometric mapping with statistical analysis and simulation, this paper develops a roadmap of policy relevance for the successful deployment of blockchain in energy markets.

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APPENDIX

Table 1. Yearly Publication Counts

Year	Publications	Citations	Avg Citations per Paper	Citations per Year
2018	2	351	175.50	39.00
2019	6	515	85.83	64.38
2020	18	1,629	90.50	232.71
2021	22	1,839	83.59	306.50
2022	36	1,129	31.36	225.80
2023	34	764	22.47	191.00
2024	54	523	9.69	174.33
2025	45	64	1.42	32
2026	1	-	-	-

Source: created by the authors

Table 2. Keyword (Occurrence and Total Link Strength)

Cluster	Keywords	Occurrence	TLS
Renewable Energy and Sustainability	Sustainability	57	281
Renewable Energy and Sustainability	Sustainable Development	31	182
Renewable Energy and Sustainability	Energy Efficiency	15	105
Renewable Energy and Sustainability	Renewable Energy	14	96
Renewable Energy and Sustainability	Climate Change	7	40
Blockchain Adoption Frameworks & Governance	Blockchain Adoption	71	341
Blockchain Adoption Frameworks & Governance	Technology Adoption	67	344
Blockchain Adoption Frameworks & Governance	Decision Making	25	136
Blockchain Adoption Frameworks & Governance	Innovation	23	123
Blockchain Adoption Frameworks & Governance	Stakeholder	12	66
Blockchain Adoption Frameworks & Governance	Governance Approach	5	28
Digital Technologies and Integration	Blockchain	152	614
Digital Technologies and Integration	Blockchain Technology	52	252
Digital Technologies and Integration	Artificial Intelligence	17	98
Digital Technologies and Integration	Smart Contracts	15	53
Digital Technologies and Integration	Distributed Ledger Technology	12	72
Digital Technologies and Integration	Digitization	11	67
Digital Technologies and Integration	Digital Transformation	10	57

Source: created by the authors

Table 3. Keywords Clusters

Cluster	Keywords (Top Examples)	Notes
Renewable Energy & Sustainability	Renewable energy, energy efficiency, sustainability, sustainable development, climate change, green economy, recycling	Focus on energy transition, climate policy, and sustainable practices.
Adoption Frameworks & Governance	Blockchain adoption, technology adoption, innovation, decision making, stakeholder, strategic approach, governance approach	Emphasis on organizational readiness, adoption models, and policy frameworks.
Digital Technologies & Integration	Blockchain; blockchain technology; AI; machine learning; smart contract; smart grid; digital transformation; digitization; distributed ledger technology	Integration of blockchain with Industry 4.0 and digital ecosystems.

Source: created by the authors

Table 4. Number of publications in co-authorship by country (2018-2026).

R	Co-authorship by Countries	Number	% of 218	Citations	TLS	Average Citations per Paper
1	China	60	22.47%	1,302	27	21.7
2	United Kingdom	22	8.24%	1,525	29	69.3
3	Malaysia	22	8.24%	647	20	29.4
4	Saudi Arabia	20	7.49%	540	31	27.0
5	India	19	7.12%	728	21	38.3
6	Italy	19	7.12%	642	5	33.8
7	United States	16	5.99%	906	12	56.6
8	South Korea	13	4.87%	923	10	71.0
9	Taiwan	11	4.12%	548	18	49.8
10	Turkey	9	3.37%	129	14	14.3
11	Australia	8	3.00%	446	6	55.8
12	Pakistan	7	2.62%	237	12	33.9
13	South Africa	7	2.62%	94	5	13.4
14	Canada	7	2.62%	210	7	30.0
15	Germany	6	2.25%	421	3	70.1
16	Portugal	6	2.25%	57	2	9.5
17	Qatar	6	2.25%	241	2	40.2
18	Iran	5	1.87%	51	10	10.2
19	Spain	5	1.87%	143	2	28.6

Source: created by the authors

Table 5. Publications by Organization.

R	Organizations	Country	Number	% of 218	Citations	TLS
1	Universiti Teknologi Malaysia	Malaysia	5	27.78%	315	2
2	University of Johannesburg	South Africa	5	27.78%	50	2
3	İstinye Üniversitesi	Turky	4	22.22%	23	39
4	Yuan Ze University	Taiwan	4	22.22%	23	39

Source: created by the authors

Table 6. Top Article by Age Normalized Citations.

Title	Authors	Journal	Year	Citation	Citation per Year	In-text Citations
Convergence of blockchain and artificial intelligence in IoT networks for the sustainable smart city	Singh S.; Sharma P.K.; Yoon B.; Shojafar M.; Cho G.H.; Ra I.-H.	Sustainable Cities and Society	2020	441	63.00	[20]
Blockchain technology adoption, architecture, and sustainable agri-food supply chains	Saurabh S.; Dey K.	Journal of Cleaner Production	2021	409	68.17	[30]
Incorporating a seller/buyer reputation-based system in a blockchain-enabled emission trading application	Khaqqi K.N.; Sikorski J.J.; Hadinoto K.; Kraft M.	Applied Energy	2018	340	37.78	[23]
The Carbon Footprint of Bitcoin	Stoll C.; Klaaßen L.; Gallersdörfer U.	Joule	2019	332	41.50	[31]
Blockchain technology adoption behavior and sustainability of the business in tourism and hospitality SMEs: An empirical study	Nuryyev G.; Wang Y.-P.; Achyldurdyyeva J.; Jaw B.-S.; Yeh Y.-S.; Lin H.-T.; Wu L.-F.	Sustainability (Switzerland)	2020	223	31.86	[19]
Artificial Intelligence and emerging digital technologies	Lyu W.; Liu J.	Applied Energy	2021	222	37.00	[18]

Title	Authors	Journal	Year	Citation	Citation per Year	In-text Citations
in the energy sector						
Factors affecting the organizational adoption of blockchain technology: Extending the technology–organization– environment (TOE) framework in the Australian context	Malik S.; Chadhar M.; Vatanasakdakul S.; Chetty M.	Sustainability (Switzerland)	2021	153	25.50	[22]
Blockchain technology adoption in smart learning environments	Ullah N.; Al-Rahmi W.M.; Alzahrani A.I.; Alfarraj O.; Alblehai F.M.	Sustainability (Switzerland)	2021	148	24.67	[21]
A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development	Liu W.; Shao X.-F.; Wu C.-H.; Qiao P.	Journal of Cleaner Production	2021	144	24.00	[33]
Factors affecting organizations' resistance to the adoption of blockchain technology in supply networks	Choi D.; Chung C.Y.; Seyha T.; Young J.	Sustainability (Switzerland)	2020	141	20.14	[34]
Discovering research trends and opportunities of green finance and energy policy: A data-driven scientometric analysis	Wang M.; Li X.; Wang S.	Energy Policy	2021	140	23.33	[28]
Digitalization of agri-cooperatives in the smart agriculture context. Proposal of a digital diagnosis tool	Ciruela-Lorenzo A.M.; Del-Aguila-Obra, A.R.; A., Padilla-Meléndez, A.; Plaza-Angulo, J.J.	Sustainability (Switzerland)	2020	115	16.43	[35]
Block chain infrastructure and growth of global power consumption	Denisova V; Mikhaylov AY; Lopatin E	International Journal of Energy Economics and Policy	2016	111	13.88	[36]
On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: Techno-economic-social considerations	Kobashi T; Yoshida T; Yamagata Y; Naito K; Pfenninger S; Say K; Takeda Y; Ahl A; Yarime M; Hara K	Applied Energy	2020	101	14.43	[37]
Sustainable supply chains with blockchain, IoT and RFID: A simulation on order management	Varriale V; Cammarano A; Michelino F; Caputo M	Sustainability (Switzerland)	2021	99	16.50	[38]
Barriers to Blockchain Adoption in the Circular Economy: A Fuzzy Delphi and Best-Worst Approach	Rejeb A; Rejeb K; Keogh JG; Zailani SHDM	Sustainability (Switzerland)	2022	95	19.00	[39]
Blockchain Adoption for Sustainable Supply Chain Management: Economic, Environmental, and Social Perspectives	Munir MA; Habib MS; HUSSAIN AHMB; Shahbaz MA; Qamar A; Masood T; Sultan M; Abbas MM;	Frontiers in Energy Research	2022	95	19.00	[40]

Title	Authors	Journal	Year	Citation	Citation per Year	In-text Citations
	Imran SM; Hasan M					
Blockchain technology for distributed generation: A review of current development, challenges and future prospect	Yap KY; Chin HH; Klemeš JJ	Renewable and Sustainable Energy Reviews	2023	86	21.50	[41]
Theoretical Perspectives on Sustainable Supply Chain Management and Digital Transformation: A Literature Review and a Conceptual Framework	Stroumpoulis A; Kopanaki E	Sustainability (Switzerland)	2022	80	16.00	[42]

Source: created by the authors

Table 7. Number of publications by journal (2018-2026)

R	Publication by a Journal	Number	% of 218
1	Sustainability (Switzerland)	2,900	48.68%
2	Journal of Cleaner Production	962	16.15%
3	Applied Energy	706	11.85%
4	Sustainable Cities and Society	473	7.94%
5	Energies	387	6.50%
6	Renewable and Sustainable Energy Reviews	179	3.00%
7	Frontiers in Energy Research	96	1.61%
8	Smart and Sustainable Built Environment	72	1.21%

Source: created by the authors

Table 8. Publications by author.

R	Authors	Number	% of 218	Citations
1	Babaei, Ardavan	4	1.83%	23
2	Tirkolaee, Erfan Babaee	4	1.83%	23
3	Mohandes, Saeed Reza	3	1.38%	132
4	Mugahed Al-Rahmi, Waleed Mugahed	3	1.38%	217
5	Prasath Kumar, V. R.	3	1.38%	132
6	Singh, Atul Kumar	3	1.38%	132

Source: created by the authors

Table 9. Bibliographic Coupling by author.

R	Authors	Number	Citations	TLS
1	Mohandes, Saeed Reza	3	132	62
2	Prasath Kumar, V. R.	3	132	62
3	Singh, Atul Kumar	3	132	62
4	Cammarano, Antonello	2	177	59
5	Caputo, Mauro	2	177	59
6	Michelino, Francesca	2	177	59
7	Varriale, Vincenzo	2	177	59
8	Babaei, Ardavan	4	23	58
9	Tirkolaee, Erfan Babaee	4	23	58
10	Andreoulaki, Ioanna	2	11	43
11	Marinakis, Vangelis	2	11	43
12	Papapostolou, Aikaterini	2	11	43
13	Alzahrani, Ahmed Ibrahim	2	193	40
14	Mugahed Al-Rahmi, Waleed Mugahed	3	217	40
15	Ullah, Nazir	2	193	40

Source: created by the authors

Table 10. Monte Carlo Simulation Robustness

Simulation Runs	Modularity Score Range	Silhouette Coefficient Variations	Cluster Membership Stability
1,000	0.72-0.78	±0.03	>90% preserved

Source: created by the authors

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