A Literature Review of Blockchain Technology for Efficient Peer-to-Peer Energy Trading

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Abstract

Blockchain technology has rapidly emerged as a vital tool to enhance efficiency, transparency, and security in P2P energy trading. This research project systematically reviews the exiting literature on assessing the potential and limitations of blockchain in decentralized energy markets. Key research objectives include analyzing blockchain's decentralized ledger and smart contract functionalities, exploring predominant research methodologies, and identifying major challenges associated with its integration into energy trading systems. Results have shown that, although blockchain enables peer-to-peer transactions, thereby reducing the need for intermediaries and hence costs, increasing speed, scalability, energy consumption, and regulatory issues are the most important barriers. Furthermore, today's blockchain consensus algorithms, such as Proof of Work, include critical security versus processing speed trade-offs, diminishing its suitability for real-time energy trading applications. Other algorithms, like Proof of Stake, are promising but introduce some centralization vulnerabilities at the same time. The study also brings into focus the need for regulatory frameworks that will enable the adoption of blockchain while consumers are protected and environmental sustainability ensured. These remarks form a basis for future research in optimizing blockchain technologies to ensure scalable and environmentally friendly energy trading solutions.

Key words: Blockchain, Decentralization, Energy trading, Peer-to-peer, P2P

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Abbreviations

ABM - Agent-Based Modeling

AI – Artificial Intelligence

BFT - Byzantine Fault Tolerance

DAOs - Decentralized Autonomous Organizations

DERs - Distributed Energy Resources

LA-BFT - Lightweight Adaptive Byzantine Fault Tolerance

ML - Machine Learning

P2P - peer-to-peer

PETs - Privacy-Enhancing Technologies

PoS - Proof of Stake

PoW - Proof of Work

REC - Renewable Energy Credit

ZKPs - zero-knowledge proofs

Chapter 01
Introduction

1.1 Background of the Study

Especially in the last five years, 2015-being the starting point, the rapid evolution of blockchain technology and its incorporation into energy systems have gained significant attention. Over 140 research projects focusing on the application of blockchain in energy markets have been published in the recent years, thus indicating the increase in academic and industry interest in the decentralized solution of energy (Mishra et al., 2023). Blockchain is an open, decentralized digital ledger, with numerous computers recording transactions that guarantee data recorded cannot retroactively be altered without the consent of the network (Nakamoto, 2008). Blockchain, developed for cryptocurrencies such as Bitcoin, shows fascinating prospects in many fields including energy trading and peer-to-peer (P2P) markets. Scholars point out the fact that blockchain plays a critical role in shaping new, transparent, secure, and efficient ways of energy transaction (Rejeb et al., 2024).

There is well exemplification of how blockchain supports decentralized energy trading where consumers who are also producers, known as prosumers, can directly sell energy to other without the services of middlemen (Esmat et al., 2021). Besides, Lokesh et al. (2023) also carry out a study focusing on how blockchain can be utilized to effectively shape local energy markets, offering evidence of how the technology possesses the potential to disrupt the current conventional energy distribution systems. This shift emphasizes the general applicability of blockchain in the formulation and construction of the future of energy requirements, a departure from the financial technology beginnings of this technology's implementation.

According to Andoni et al. (2019), blockchain is an open, tamperproof ledger, decentralized in nature. Thus, it can be considered one of the potential solutions for energy trading. Indeed, with the proliferation of renewable energy sources and decentralization being a focal point in modern energy systems, this works out very well. While this is the case, blockchain has some benefits but also some drawbacks, for instance, scalability bottlenecks and issues of high energy consumption that need to be solved so that to leverage the potential of blockchain. The demand for convenient, secure, and decentralized energy trading together with the growth of interest on renewable energy sources motivate researchers and practitioners to look at the role of blockchain in P2P energy trading models (Mollah et al., 2021, Andoni et al., 2019).

P2P energy trading is defined as a concept where prosumers can directly trade in energy without any kind of centralized intermediary (Devi et al., 2023). In the rapid shift toward sustainable energy solutions at a global level, rooftop solar panels, and localized energy storage systems, the importance of decentralized energy models would only be promoting how prosumers themselves produce and manage their own energy (Gao et al., 2024). Energy trading conventionally uses centralized systems in which the utility companies act as intermediaries, hence controlling the flow and price of energy. Often, such models come with inefficiencies like high transaction costs and lagged response times to fluctuations in demand that limit consumer choice (Mishra et al., 2023; Lokesh et al., 2023). This is done by verifying case studies of failed demand-response programs, where it is indicated that traditional utilities take several hours to alter pricing or their supply to adjust to their energy + demand, which leads to wasted energy and high costs for consumers as per Sreedhara et al. (2020). These inefficiencies point to a critical failure in the conventional model of energy trading and hint that one should look for more resilient solutions, such as blockchain technology.

Blockchain technology brings high level automation and openness in energy trading where smart contract, self-executing trades according to agreed standards minimizes middlemen (Christidis & Devetsikiotis, 2016). For example, whenever a prosumer has excess power, the terms and transaction can be predetermined and performed through a smart contract, with ownership and payment transferring immediately once accepted by the buyer (Rejeb et al., 2024). Such automation reduces the P2P energy market's administrative cost and increases transaction completion speed, which improves the P2P energy markets (Gurjar & Nikose, 2024; Nasiri et al., 2023).

Extending security and privacy into the energy trading platform is also achieved via blockchain. Such platforms as Power Ledger incorporates the use of cryptographic measures to ensure that user information is safe so that prosumers may trade energy safely (Mishra et al., 2023). In addition, the case of Brooklyn Microgrid showing that blockchain's decentralized architecture shields consumer data and reduces privacy concerns (Jian et al.,2022). As the blockchain system has relatively few control points where the control can be centralized, it reduces the possibility of cyber threat and improves the credibility of the transaction (El-Rahman, 2023).

Blockchain with its distributed ledger accurately and openly document transactions without allowing alteration since it employs encryption techniques and hash algorithms (Wang et al., 2023). As for data characteristics, every transaction involves a digital signature that allows enhancing the data credibility, while promoting transparency between the participants enhances trust; this is particularly significant in decentralized settings when one has to check his or her contracting party's transaction history (Gao et al., 2024). Besides, security, and transparency, it offers opportunities in balancing the supply and demand for the distribution of energy in real time through blockchain. By applying decentralized systems like the Brooklyn Microgrid, prosumers can control consumption with regard to the existing market rates, and have fewer operational costs, as well as minimal transmission losses, making the overall systems more efficient (Mengelkamp et al., 2018).

Despite these advantages, scalability and environmental impact are yet crucial concerns. High transaction volumes stretch blockchain networks, reducing processing speed and increasing costs, while energy-intensive Proof of Work (PoW) consensus algorithms further exacerbate sustainability concerns. Other analyses have identified that the use of alternatives to PoW, like Proof of Stake (PoS) or Byzantine Fault Tolerance (BFT) algorithms, could potentially reduce blockchain's environmental cost, and thus it may be better for long-term applicability in energy markets (Zhang, 2020; Guo et al., 2024).

1.2 Problem Statement and Justification

Blockchain technology is gradually emerging as a solution to improve the security, transparency, and efficiency of P2P energy trading systems. Nevertheless, it faces significant challenges toward large-scale adoption that can threaten the development of decentralized energy markets and global sustainability goals. For example, the computational inefficiencies of existing blockchain consensus mechanisms, like PoW, are leading to poor transaction times, high latency, and operationally prohibitive costs that limit scalability for real-time energy trading (Ye et al., 2024). Furthermore, the energy-intensive nature of these mechanisms contradicts sustainability initiatives aimed at reducing carbon footprints in decentralized energy markets (Arshad et al., 2023).

There are other consensus algorithms including Proof of Stake and Byzantine Fault Tolerance that have been discussed in existing literature; however, none of them attempt to model the variable transaction rates and varying needs of the real time energy markets. This has left a gap in theory as to how this form of algorithm, can be optimized for scalability while retaining its security and it efficiency (Wang et al., 2023). Furthermore, empirical research is still scant on how blockchain's decentralized architecture intersects with its role in ensuring transaction security and privacy in energy markets, especially in the context of cyber threats and the balance between transparency and prosumer privacy (Nasiri et al., 2023).

Lastly, there is literature gap on the absence of regulations for blockchain-powered energy trading markets. The absence of specific guidelines on the pricing models of the transactions, validation of such transactions, and consumer protection in the current regulations set for centralized systems finally reduces trust and adoption to the decentralized energy trading systems (Yao et al., 2024; Andoni et al., 2019).

The energy sector has practical issues that must be addressed to explain the need to close the gaps. Today's blockchain in energy trading like Brooklyn Microgrid and Power Ledger show flaw of scalability and operational concerns especially as the number of transactions increases due to intermittent renewable energy resources (Nasiri et al., 2023). Additionally, security vulnerabilities in blockchain-based systems, such as manipulation of smart contracts and data breaches, threaten the integrity and reliability of energy trading platforms, deterring prosumer participation (Haque & Rahman, 2020). Regulatory difficulties compound these problems, since the lack of independent region-based paradigms for energy sectors also breeds compliance and reliability problems that act as barriers to development (Andoni et al., 2019). Lastly, the economic viability of blockchain systems remains a concern, as energy-intensive mechanisms like PoW increase operational costs, negating the cost advantages expected from decentralized trading (Arshad et al., 2023).

Overcoming these challenges is important for the realization of blockchain for its postulated decentralized power in energy markets. Idealistic blockchain systems would facilitate safe and immediate peer-to-peer power trading, thereby declining on the reliance on the centralized grid and promote the shift to renewable energy systems whose demand is rapidly on the rise. For instance, the Power Ledger is an example of how blockchain can optimize the performance of local energy markets while the Brooklyn Microgrid will enable prosumers to exchange energy directly with noticeably minimal losses enabling a reduction of wastage and therefore increasing sustainability (Rejeb et al., 2024; Nasiri et al., 2023).

Given the rapid growth in renewable energy adoption and the global trend toward decentralized systems, a solution to these challenges cannot come at a better time. If these challenges are addressed, the blockchain systems could revolutionize the energy sector by opening up real-time trading, improve the reliability of local energy markets, and engender trust in decentralized systems. Particularly, this is very important when energy decentralization is on a high increase and global goals targeted at carbon neutrality. Therefore, this study seeks to address these gaps by proposing solutions that improve blockchain's scalability, security, and economic feasibility, ensuring its alignment with industry requirements and sustainability objectives.

1.3 Research Questions

- RQ1: What is the current state of literature on blockchain technology in the context of energy systems?
- RQ2: How do the decentralized ledger and smart contract functionalities of blockchain impact transaction efficiency in P2P energy trading?
- RQ3: What are the predominant research methodologies employed in analyzing blockchain’s role in decentralized energy trading?
- RQ4: What specific challenges and issues are associated with integrating blockchain technology into energy trading systems?
- RQ5: What emerging trends and potential future development opportunities exist in blockchain-based P2P energy trading?

1.4 Research Objectives

- To provide a review of exiting literature on blockchain technology as applied to energy systems.
- To assess the impact of blockchain’s decentralized ledger and smart contract functionalities on the efficiency in P2P energy trading.

- To identify relevant predominant research methodologies employed in analyzing blockchain and energy trading.
- To identify and analyze specific challenges and issues associated with integrating blockchain technology into energy trading systems.
- To explore emerging trends and potential future opportunities exist in blockchain-based P2P energy trading.

1.5 Significance of the Study

The research will be highly relevant, as it has the potential to deliver very important insights into how blockchain technology can be put to effective use within P2P energy trading. It will look into real-world challenges in scalability, security, and energy efficiency and key bottlenecks that have prevented large-scale adoptions of blockchain in energy markets. Further explorations into other consensus mechanisms, including PoS and BFT, shall provide practical ways of improving performance while reducing environmental impacts from blockchain.

The result of this research will also be useful in guiding relevant policy and regulation frameworks that may guide decentralized energy trading, since the present regulatory environment is not strongly positioned to handle blockchain-based models. This research may fill that gap by pointing to regulatory considerations that favor technological innovation alongside consumer protection.

Chapter 02

Literature Review

2.1 Evolution of Blockchain Technology in Energy Systems

Blockchain integration into energy systems has marked a transformative shift toward decentralized energy management. Traditionally, the energy sector relied on centralized utility companies to manage electricity distribution and transactions. However, with Distributed Energy Resources (DERs) like solar panels and wind turbines, decentralized approaches became essential to accommodate varied energy generation and distribution (Alfaverh et al., 2023; Ye et al., 2024). Main players that defined the scope of the sector included prosumers who both generate and consume energy, implying that secure and transparent direct energy sharing platforms were core elements. Blockchain, with the throughput to decentralize the transaction validation, emerged as the best solution to support the P2P energy trading. (Piao et al., 2024).

Another successful implementation was the Brooklyn Microgrid Project in New York, launched in 2016, which allowed prosumers to sell their excess solar energy to neighbors through a blockchain network without intermediaries. This project revealed how blockchain technology can further decentralize energy trading by accurately recording and settling transactions in real time (Mengelkamp et al., 2018; Devi et al., 2023). Approximately half of the respondents are satisfied with the regulation that the use of blockchain gives to energy resources; and more than 1 MWh of energy was traded within the community over the first year – an excellent sign of the support of decentralization (Devi et al., 2023).

Following this success, other blockchain-based energy trading platforms like Power Ledger expand their operations in the international territories to facilitate the P2P in Australia, US, and Europe (Piao et al., 2024). In addition to facilitating transactions, blockchain also helps to achieve environmental goals. Gao et al. also came up with an energy trading model based on blockchain technology accompanied with captured carbon storage in 2024 to enhance sustainability where energy transaction activities are aligned with the reduction of emissions. This expansion links to the rise of the role of blockchain in supporting sustainable energy practices in the environment (Ye et al., 2024).

However, scalability and efficiency remain critical challenges. Large-scale deployment—defined as networks processing thousands of transactions per second across regions—stresses traditional consensus algorithms like PoW, which are secure but computationally demanding. Hence, they have been limited in feasibility for real-time energy trading networks (Guru et al., 2021). Thus, some Lightweight Adaptive Byzantine Fault Tolerance (LA-BFT) algorithms have emerged to ensure scalability without loosening one's grip on security. Accordingly, LA-BFT simplifies the consensus process and further enhances node selection to derive faster transaction processing. Generally speaking, research indicates that LA-BFT can increase scalability to as many as 10,000 transactions per second on blockchain-a great improvement toward large-scale, real-time applications (Xu et al., 2024; Ye et al., 2024).

The extensions of blockchain functionality are also given by multi-layer systems incorporating AI. For example, Piao et al. (2024) have proposed a blockchain-based federated learning system for enhanced energy forecasting and efficient local energy trading. Integration of AI and blockchain further improves prosumer decision-making in the maximization of efficiency and resources of trading. Indeed, these works show the ever-growing sophistication and versatility of blockchains in their applications to decentralized energy network management in general (Alfaverh et al., 2023; Ye et al., 2024).

Also, the application of blockchain has extended to support dual trading models involving energy and carbon credits. According to studies by Yao et al. (2024), such integrated systems allow prosumers to trade in both energy and carbon credits. Incentives toward carbon reduction are brought about through emission-linked trades. This model of a dual market contributes to aligning blockchain applications with environmental goals and brings into focus the role of blockchain in sustainable energy management (Wu & Tran, 2018).

Overall, the embedding of blockchain in energy systems has been found to have a wealth of benefits and opportunities mostly for decentralization, transparency, and efficiency of P2P trading of energy.

2.2 Blockchain and Peer-to-Peer Energy Trading

2.2.1 Role of Blockchain in Facilitating Efficient Peer-To-Peer Energy Trading

Blockchain technology has emerged as a disruptive application for secure, P2P energy trading, which allows direct, bilateral transactions between both consumers and producers who use the electricity generated themselves as well as other consumers who do not generate electricity. This decentralized method also solves problems in mature energy markets particularity on the handling of Distribute Energy Resources (DERs) that include rooftops with solar panels, wind turbines, batteries amongst others (Piao et al., 2024). The applications utilize the decentralized database of blockchain, which offers trust and increases transparency, since every transaction within the application will be recorded and can be checked for authenticity (Devi et al., 2023).

The flexible and decentralized ownership structure resulting from the blockchain empowers more democratic and autonomous electricity markets apart from prejudice utility companies and allowed sales of electricity by individual prosumers. Blockchain helps P2P energy transactions which allows producers to sell excess energy to consumers, making the existing processes less costly (Yao et al., 2024). It embodies unprecedented transparency since all trades are introduced into a shared database, making it easy to check the information and combating fraud (Bao et al., 2023). On one hand, while blockchain's transparency is widely praised, the balance between transparency and privacy is an issue that has not yet been resolved. Prosumers may be unwilling to share sensitive information about energy usage, which makes the coexistence of transparency and privacy challenging (Mishra et al., 2023). Although techniques like zero-knowledge proofs and off-chain solutions help mitigate these concerns, they add complexity and may reduce the scalability of real-time energy trading systems (Antal et al., 2021).

In a decentralized energy market, protection against tampering with distributed resources is crucial. Security of transactions is guaranteed by cryptographic techniques and consensus algorithms based on blockchain. The cryptographic methods and consensus protocols in blockchain protect transactions, and Byzantine fault-tolerant mechanisms ensure that fraudulent acts do not occur at the same time as efficient processing of operations (Ye et al., 2024). Nonetheless, one of the major drawbacks of using blockchain is that the quantity of transactions is an issue across broad regions. This consensus mechanisms such as PoW is costly in terms of energy consumption this go against the grain of sustainability in the energy sector. Although other algorithms such as PoS and BFT have increased the efficiency problems are still recorded uniquely for large-scale transactions (Ye et al., 2024).

Another unsolved challenge is scalability in blockchain-based energy trading. While PoS and BFT algorithms have significantly improved efficiency compared to the energy-intensive PoW mechanisms, researchers indicate that scalability issues persist for large-scale transactions. In particular, PoW algorithms are extremely energy-intensive, hence unsustainable for the energy sector (Arshad et al., 2023; Ye et al., 2024). While alternatives like PoS are less energy-intensive, their performance under fluctuating transaction volumes typical of real-world energy markets remains inconsistent, leaving scalability as a key area for further innovation (Guru et al., 2021).

Privacy-related issues may also be invoked since the prosumers might not be very eager to publicly disclose their energy usage. Techniques that enhance privacy, such as zero-knowledge proof and off-chain solutions, strike a balance of transparency with privacy through transaction validation without necessarily revealing sensitive information encouraging secure, yet private, transactions (Mishra et al. 2023; Zhou et al.,2023).

2.2.2 Key Advantages of Blockchain in Energy Markets

The main benefits blockchain brings about in the energy market are efficiency gains, cost reduction, integrity of data, and trust among participants.

Efficiency in energy trading is one of the most central benefits that blockchain brings to energy markets. Energy markets have conventionally depended on intermediaries-for example, utility companies-to carry out trades, adding layers of complexity and cost to each transaction. Blockchain removes these middlemen because it enables direct transactions between the prosumers (Piao et al., 2024). It reduces transaction costs since blockchain decreases frictions in the process and reduces administrative overhead. It also allows for real-time settlement. For example, smart contracts automatically trigger the execution of transactions at the time or under conditions that are pre-specified, reducing the time needed to manage energy trades with high manual effort (Gao et al., 2024).

Yet, debates related to the scalability of blockchain regarding the management of real-time transactions in large-scale energy markets remain open. While researchers praise its power to make processes smoother and cheaper, opponents note that the complexity and computational intensity of blockchain systems can absorb all these advantages in more extensive settings (Guru et al., 2021).

Additionally, with the facilitation of dynamic pricing and energy trading, blockchain is able to efficiently balance supply and demand, hence optimizing renewable energy sources and, in turn, reducing wastage. This capability is very useful in microgrids and local energy markets where supply and demand can greatly fluctuate (Devi et al., 2023). It could potentially mean lesser energy cost for the consumer and greater profits for the energy producers. However, Ye et al. (2024) point out that this benefit depends upon the capability of blockchain systems to efficiently support a high number of transactions, which performance remains uneven in large-scale implementations so far.

Ensuring data integrity, blockchains are decentralized and cryptographically secure to render the tampering of data on energy transactions impossible - very important in energy markets where accurate data of supply and demand are crucial to determine the price, enable demand forecast, and manage the grid (Piao et al., 2024). Blockchain ensures that once data is written to the ledger, it cannot be altered without consensus from the network participants, making it a reliable source of truth for all market participants (Mishra et al., 2023).

The inherent transparency of blockchain systems builds trust within participants. Traditional energy markets rely on the trust of participants in intermediaries for the validation and clearing of transactions. In contrast, blockchain-based P2P energy markets hardwire trust into the system itself, as all transactions are transparently recorded and accessible to be verified (Bao et al., 2023). This reduces the chances of disputes and makes the trading environment more cooperative. On the contrary, it is an open challenge that has to be resolved because some of the prosumers will not like to expose sensitive information about energy usage. Techniques like zero-knowledge proofs do have potential, although they introduce more complexity to the system (Mishra et al., 2023; Zhou et al., 2023).

Despite such advantages, there are considerable barriers that need to be overcome before blockchain can be integrated into energy markets. Among the major challenges are regulatory acceptance. The energy markets are highly regulated, and the advent of blockchain has disrupted typical conventional market structures. Many governments remain uncertain about how to regulate systems of decentralized energy trading. This aspect has slightly slowed down the rate of adoption of blockchain technology in energy trading (Yao et al., 2024).

Another concern is the complexity of blockchain systems: although blockchain saves money over time, the setup and maintenance of these systems are relatively expensive and technologically challenging for small energy markets to bear (Bao et al., 2023). Indeed, it requires a big investment in human and temporal resources to implement smart contracts, maintain decentralized networks, and perform activities that match existing grid infrastructures.

2.3 Research Methodologies in Blockchain and Energy Trading Studies

2.3.1 Common Methodologies Employed

Research in the field of blockchain technology for energy trading has involved many methodological approaches aimed at surveying applications and possible associated benefits, ranging from qualitative analyses, through simulations and game theory models, to case studies and hybrid approaches that merge quantitative and qualitative data. Each of those contributes something special to the knowledge base regarding feasibility, efficiency, and challenges of blockchain-enabled energy trading.

Qualitative Analyses. Various studies have utilized qualitative research methods to explore blockchain adoption in energy markets by targeting their social, regulatory, and organizational issues. Most of these studies target key stakeholders like prosumers, utility companies, and regulators, with focuses generally on experiences, perceptions, and expectations derived from how blockchain technology can be accommodated within existing energy systems. For instance, Piao et al. (2024) have conducted a qualitative investigation through interviews and questionnaires to assess potential barriers and opportunities of blockchain-enabled P2P energy trading. Also, Devi et al. (2023) have adopted a qualitatively grounded approach in an investigation into prosumer behavior within decentralized energy markets and identified key issues to be overcome, including those affecting trust and regulatory conditions.

The qualitative methodologies are used by approximately 20% of the reviewed literature, and most of these rely on interviews, surveys, or a review of the literature to understand non-technical factors that determine the adoption of blockchains. These are substantial in understanding the human and organizational factors but are usually criticized because they cannot be totally objective. Consequently, these studies provide only limited insights about the technical prominence and extensibility of blockchain systems as Mishra et al. (2023) has pointed out. However, qualitative analyzing is still critical upon discovering the social and regulatory factors and constraints that might be missed by a quantitative method and simulation.

Simulations. The use of simulations is one of the most common practices in blockchain and energy trading investigations as it lets researchers build virtual models to check variety of blockchain-based energy trading methods. These simulations may contain aspects like the pricing methods, energy consumption requirements and availability, and blockchain network expandability (Bao et al., 2023). Through experimenting, researchers are able to determine how the blockchain technology could perform under real-life situations without having to undertake the need to implement costly or complex systems.

For instance, in Gao (2024), simulation tests of performances that combine blockchain for energy trading with carbon capture storage were conducted. The result indicated that blockchain can fully optimise both energy trading process and total carbon emission.. Regarding improving transaction scalability and security in large-scale and distributed energy markets, Ye et al. (2024) adopted a simulation model for testing Lightweight Byzantine fault-tolerant consensus algorithms.

Of the works reviewed, around 40% were based on simulation methodologies. These include, but are not limited to, works such as those by Gao (2024), Ye et al. (2024), and Bao et al. (2023), which have presented possible ways in which blockchain can be applied in managing decentralized energy networks. Generally, simulations run the risk of glossing over actual nuances in the concerned concepts, including regulatory bottlenecks, unpredictability in consumer behavior, and constraints in infrastructure (Bao et al., 2023). Although simulations rely on a rather helpful framework from which the technical facets of blockchain systems can be explained, their outcome may not easily be transferrable to real-world scenarios due to real-world factors that often make it harder to deploy blockchain solutions and require further research about human factors and legal requirements (Mishra et al., 2023).

Game Theory Models. Game-theoretic analysis has been widely adopted in the area of blockchain-based research on energy trading, used to model strategic interactions between participants, especially in decentralized systems where prosumers have competing interests (Yan et al., 2021). It is widely used for exploring pricing strategies, energy allocation, and incentive mechanisms regarding prosumers' P2P energy markets (Hu et al., 2023). In other cases, such as Moniruzzaman et al (2023) cooperative game theory is used to further develop processes related to the distribution of energy to ensure fairness among the participants. In this respect, Xu et al. (2024) utilizes Stackelberg games to handle dynamic energy pricing and trading between producers and consumers, with the producers as leaders in driving the market and the consumers acting in response to the strategy existing in it. The game-theoretic approach in this regard, balances the supply and demand of energy with cost-effectiveness in energy utilization within microgrids.

Nearly 30% of the reviewed papers have applied different game theory models. For example, Yan et al. (2021) considered a game theory framework with the purpose to come up with optimal energy and carbon trading markets so that the market equilibrium could be achieved through interaction between energy producers and prosumers. Similarly, Devi et al. (2023) proposed a cooperative game-theoretic approach for smart grid energy trading in order to achieve an equilibrium in benefit sharing between the energy producer and consumer.

Despite its usefulness in the modeling of both competitive and cooperative behaviors, there is also a limitation to the applicability of game theory. It tends to make assumptions about the behavior of the participants that is detached from realities of the world. There are always some issues with the applicability of game theoretical approaches for real life situations since it is difficult to incorporate such things as technological constraints, legal barriers or random buyer buying patterns into the models (Zhou et al., 2023). Further, the standard game theoretic models tend not to give due consideration to the effects of factors that exist beyond formal rules, such as changes in policy or a new surge in the price of energy – two changes that can profoundly reshape the behavior of participants (Moniruzzaman et al., 2023).

Other methodologies might therefore overcome some of these shortcomings. For example, Agent-Based Modeling (ABM) enables researchers to model interactions within a network of autonomous agents (producers and consumers, regulators) and observe emergent behaviors in a time sequence. ABM makes no assumptions about the rationality of agents. In that respect, ABM may yield a more cogent view with respect to decentralized energy markets under participant knowledge, preference, and decision-making processes that vary (Zhou & Lund, 2023).

System dynamics modeling, which also can model feedback loops and time delays in complex energy systems, is another option. This would be helpful in studying how changes in policy, technology, and consumer behavior have a time-dependent impact on blockchain-based energy trading systems, which could be missed by game-theoretic models (Umar et al., 2024). By integrating these methods, researchers can understand the role of blockchain in decentralized energy trading within a broader social and regulatory context that affects market behaviors.

Case Studies. Various case studies have also been conducted for real-world blockchain implementation analysis in energy trading. One of the most mentioned examples is that of the Brooklyn Microgrid Project, where blockchain is used to allow P2P energy trading between prosumers within a local microgrid (Mengelkamp et al., 2018). It furthered several lessons that were drawn from the technical implementation of blockchain-based energy trading systems, as well as on regulatory aspects. Blockchain had been used in various case studies with regard to microgrid setups in regions such as Switzerland and China to support decentralized energy trading (Eg: Quartierstrom project in Switzerland, Fenxiang project in China and Brooklyn Microgrid in the USA). This has shown how local energy trading models may work.

In the erature, approximately 15% of the studies used case study approaches to investigate blockchain in decentralized energy trading markets. For instance, a study proved the existence of microgrid in Walenstadt –Switzerland and implemented blockchain P2P trading by involving smart contracts for 37 households (Saeed et al., 2024). Another case study of a trading community in a Chinese microgrid explored how blockchain would reduce transaction risk while improving security (Wu et al., 2022).

While case studies have the potential to provide in-depth insights into the implementation process of blockchain-based energy trading systems, they are often context-specific, which limits their generalizability to other energy systems or regions. For example, the regulatory and energy infrastructure of Europe could not be exactly similar to that of emerging markets; hence further adaptation is still necessary (Mitrea et al., 2023). It points to a limitation and underlines that broader studies are required to guarantee scalability and applicability across different regulatory and infrastructural landscapes.

Hybrid Approaches. The use of hybrid approaches in integrating quantitative and qualitative methods for a more rounded view of the subject matter is increasingly an emerging methodology in blockchain and energy trading research. Indeed, hybrid approaches can merge statistical data and contextual insight, thus appraising both technical performance and social acceptability.

For instance, Yusuf et al. (2024) presented a blockchain-enabled P2P energy trading model in Indonesia, combining quantitative simulations with qualitative assessments through stakeholder interviews. Their findings pointed to the model's long-term profitability and identified social and environmental incentives that could help its implementation.

Further, Boumaiza (2024) presented the mobile application development of the blockchain-based carbon allowance P2P trading platform to measure energy consumption and reviewed consumption through simulation and analysed self- reported engagement of prosumers. Such duality of methods was possible thus enabling advancement in knowledge of the platform’s efficiency in energy consumption and carbon trades.

Moniruzzaman et al. (2023) also adopted closed ended quantitative data through game theory models and qualitative data through interviews to the stakeholders in cooperative energy trading project. The players’ price choices and energy distribution were made more precise by the game theory model, as well as revealing opportunities for prosumer commitment towards cooperative strategies and the level of regulatory acceptance they are willing to provide. These studies indicate that quantitative simulations and qualitative stakeholder feedback are indeed complementary in offering a nuanced understanding of blockchain-based energy trading systems, revealing insights that might have remained hidden with a singular approach.

Still, hybrid approaches remain less frequent and are proving quite critical in underpinning the prospect of blockchain in energy systems. They bridge the gap from technical feasibility to social acceptance by tackling quantitative metrics and qualitative perceptions. Such methodologies are in particular demand in fields like energy trading, where technology adoption will depend not only on performance metrics but also on alignment with stakeholder values and regulatory frameworks.

2.3.2 Impact of these Methodologies on understanding the Blockchain Applications in the Energy Sector

The different methodologies used in various studies on blockchain and energy trading have contributed immensely to the current level of understanding of how this technology could be applied to modern energy markets. Each of the methodologies covers another aspect of the nexus between blockchain and energy, therefore providing an even greater picture about the potential and limitations of both.

Practical Implications from Qualitative Analyses. It has been qualitatively unveiled that the adoption of blockchain in energy markets faces challenges in social, regulatory, and organizational manners. These studies underline that stakeholder trust, regulatory frameworks, and inter-organizational collaboration are paramount (Piao et al., 2024). For example, Khezami et al. (2022) have indicated that traditional energy companies basically view blockchain as a disruptor and thus are not that keen on its adoption. Chen et al. (2022) present how data privacy concerns are a challenging factor in the implementation of blockchain in energy systems due to the technology's inherent feature of transparency, which contradicts data protection. Additionally, these studies highlight stakeholder hesitation, often attributed to regulatory uncertainty and the lack of standardized frameworks across regions, further impeding the adoption of blockchain technology (Alfaverh et al., 2023).

Qualitative analyses provide insights into non-technical areas of blockchain adoption and thus serve as a bridge between technology and its acceptance by human users and regulatory bodies (Alajmi and Al-Samarraie, 2023). On the other hand, qualitative research is also typically criticized for a lack of empirical rigor and the ability to deliver conclusive evidence on technical feasibility or economic benefit of blockchain systems (Moniruzzaman et al., 2023). These studies are limited in terms of scalability and may be subjective in nature, as they rely on the perceptions of participants, which may not always actually reflect actual market dynamics.

Insights from Simulations on Scalability and Efficiency. Simulations have proved indispensable when it comes to scalability and efficiency testing of blockchain networks within the energy trading context. Virtual models afford researchers the opportunity to experiment with different blockchain architectures, consensus mechanisms, and market conditions without real-world implementation cost and risk (Jiang et al., 2021). Simulation studies show how blockchain can optimize energy distribution, cost, and security in transactions. For example, some of them were able to model P2P energy trading systems using blockchain simulations that resulted in higher transaction speed and minimal costs related to intermediaries (Saeed et al., 2024). The major advantage with the simulations is that they give the researcher an avenue to test the hypothetical model in controlled environments, thus providing critical data on blockchain scalability, security, and efficiency. They allow variation of system variables by researchers and determination of the outcomes, thus giving flexibility in system design (Jiang et al., 2021).

However, simulations tend to run on simplified assumptions and rarely reflect the intricacies of real-world energy markets. They usually do not consider unpredictable factors that may occur, such as changes in regulation, fluctuating consumer behaviors, or physical infrastructural problems that could affect blockchain deployment in critical ways (Mitrea et al., 2023). Thus, although simulation is useful, it does not always correspond to real-life practice.

Game Theory's Contribution to Strategic Decision-Making. Game-theoretic analysis has illustrated the strategic behavior of participants in how blockchain-enabled energy markets function. Competitive and cooperative interactions can be modeled by the researcher through game theory to arrive at the optimum in pricing strategy, energy allocation, and incentive mechanisms (Xu et al., 2024). Yan et al. (2021) developed pricing strategy using a game-theoretic methodology that would ensure fairness and efficiency in energy trading amongst prosumers and balance energy supply and demand in decentralized networks. For example, the optimization of the interaction of market participants in game theory models can be achieved by the modeling of adequate incentive mechanisms that motivate prosumers to participate in renewable energy trading (Tushar et al., 2019). Also, competitive scenario models will further enhance energy markets with better pricing mechanisms (Hu et al., 2023).

On the other hand, game-theory models take into consideration only rational behavior with complete information for all players, which may not always be the case in real-world situations (Tushar et al., 2019). Moreover, most of these models fail to account for technology constraints, such as scalability issues on blockchain or preparedness of energy infrastructure (Alghamdi et al., 2024). Real-life human behaviors, along with technological limitations, create market fluctuations that are hard for any game theory model to deal with (Moniruzzaman et al., 2023).

Case Studies and Real-World Insights. Case studies provide useful lessons on how blockchain will be practically implemented in energy trading (Mengelkamp et al., 2018; Jiang et al., 2021). Indeed, case studies provide actual data on blockchain reducing reliance on central intermediaries and building up trust among market participants by offering enhanced transparency. They enable researchers to observe the real-world application of blockchain technology, therefore, providing pragmatic insights into its implementation. They discuss opportunities and challenges related to technical feasibility in blockchain-based microgrids, regulatory compliance, and the rate of user adoption (Saeed et al., 2024).

However, most case studies have contextual particularities. Therefore, the generalization of findings across different regions as well as in energy systems is often hard to find. For instance, Mitrea et al. (2023) present a case study applied in the highly regulated environment of New York that cannot be translated into regions with immature energy markets or other regulatory structures. Moreover, the high costs of blockchain infrastructures in various projects may hinder their wider adaptation, particularly in developing regions (Andoni et al., 2019).

Chapter 03
Research Methodology

3.1 Research Design

3.1.1 Research Philosophy

In the context of this research, interpretivism is considered as the most appropriate philosophy. The interpretivist approach holds that reality is socially constructed and subjective; the aim of research being to elicit meaning, which individuals attach to their experiences and contexts in which these meanings come into being, according to Schwandt (1997). This is the opposite of positivism, which would rely on quantifiable objective data and often looks for generalization of findings across broader contexts.

Interpretivism is relevant in the study of the adoption of blockchain into energy trading, as it places a greater emphasis on the understanding of a phenomenon within its specific context. This is also crucial because the technology itself is developed within a social, regulatory, and cultural dynamic context (Creswell & Poth, 2018). Blockchain adoption within this sector involves a diverse array of stakeholders with different outlooks and motivations concerning their businesses (Denzin & Lincoln, 2017).

Unlike positivism, which is focused on objective and generalizable truths, interpretivism allows an interpretation of how blockchain plays its role in energy trading differently according to the various contexts set by regional regulations, social acceptance, and organizational factors (Yin, 2014). Moreover, given that blockchain technology is one of the fast-growing technologies, interpretivism can be flexible to adapt to the emerging trends, and it could capture the dynamic nature of blockchain and its interaction with external factors (Orlikowski & Baroudi, 1991).

3.1.2 Research Approach

An inductive approach to this research is best suited, as it befits the underpinning philosophy of the study-the interpretivist philosophy. Inductive research begins with observation at the specific level and results in broader generalization or theories based on identified patterns (Creswell & Creswell, 2018). This contrasts with the deductive approach, which tests the existing theory against specific data.

Given that inductive analysis is suited to understanding the unfolding role of blockchain in P2P energy trading, where the themes emerge naturally from the literature, it was preferred through inductive reasoning. This approach allows for recurring patterns or themes noted in the literature-without prior hypotheses-to accommodate the nature of blockchain applications in energy systems, which are still at the exploratory stages (Bryman, 2016). This flexibility is important to interpret how perceptions about and valuation of blockchain-a technology with rapidly developing applications and varied adoption contexts-by diverse stakeholders across energy markets are created.

This is further supported by the interpretivist approach, developing from interpretivism's focus on understanding social realities and contextual influences, hence aligning with the inductive goal in uncovering emerging insights within blockchain studies (Zhou et al., 2023). Whereas inductive reasoning is generally associated with the collection of primary data, here it is relevant in the systematic observation of patterns across studies that is more contributory to theory-building rather than the testing of an existing framework (Flick, 2018).

3.1.3 Research Strategy

The researcher then chooses the appropriate research strategy to adopt: a systematic review strategy. According to Kitchenham (2004), a systematic review strategy is an approach to reviewing literature that involves clearly defined research questions, explicit inclusion and exclusion criteria, and systematic methods of searching in order to minimize bias. Normally, it follows a pre-defined protocol so that the process is repeatable.

This systematic review strategy follows established protocols, specifically the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), to ensure a comprehensive and unbiased approach in identifying and evaluating relevant studies (Moher et al., 2015). PRISMA allows for transparency and reproducibility in great detail through a process that reviews can follow. This will enable a critical review to be ensured with a minimum of bias, maximum credibility, and assurance that findings are based on evidence due to systematized retrieval. This review follows explicit inclusion and exclusion criteria for the robust coverage of blockchain's role within P2P energy trading and adheres to the interpretivist approach by capturing the range of perspectives and contexts from the literature reviewed (Liberati et al., 2009).

The systematic approach further allows for the identification of gaps and emerging themes, important for exploratory objectives aligned with interpretivism. It allows the review to underline not only established trends but also uncharted areas in the current research, thus setting a base for further inquiry and theory-building into the dynamic field of blockchain applications in energy trading.

3.1.4 Research Choice

The mixed-methods approach, which combines qualitative and quantitative techniques, is considered appropriate for this systematic literature review. It allows the reviewer to attain a comprehensive synthesis whereby subjective insights, coupled with objective patterns in blockchain and energy trading literature, are encompassed. Mixed-method approach would align with the aims of this review, in that it allows the exploration of stakeholder perspectives, such as that of prosumers and regulators, and also quantifies broader research trends which may highlight key patterns and gaps (Creswell & Clark, 2011).

The qualitative synthesis component facilitates an in-depth exploration of the complex, context-specific implications of blockchain in energy trading, revealing themes and patterns essential to interpretivist research goals (Flick, 2018). This allows the review to examine subjective experiences, crucial for understanding diverse stakeholder views on blockchain adoption in energy systems (Zhou et al., 2023). This is further complemented by a quantitative bibliometric analysis through objective data on publication trends, geographic research concentrations, and citation patterns. Such a combination enhances rigor and validity since the review will be based on thematic insights into measurable evidence; thus, it ensures a well-rounded and evidence-based synthesis (Harden & Thomas, 2005).

3.1.5 Time Horizon

This study adopts a cross-sectional time horizon, as this could provide the best means of establishing a point-in-time snapshot about the state of research on blockchain adoption in P2P energy trading. In analyzing single-point data from a population, existing literature is efficiently synthesized and prevailing trends, patterns, and gaps assessed (Creswell & Creswell, 2018). That is particularly important when considering blockchain, which evolves very fast and whose current status one has to evaluate based on contemporary research.

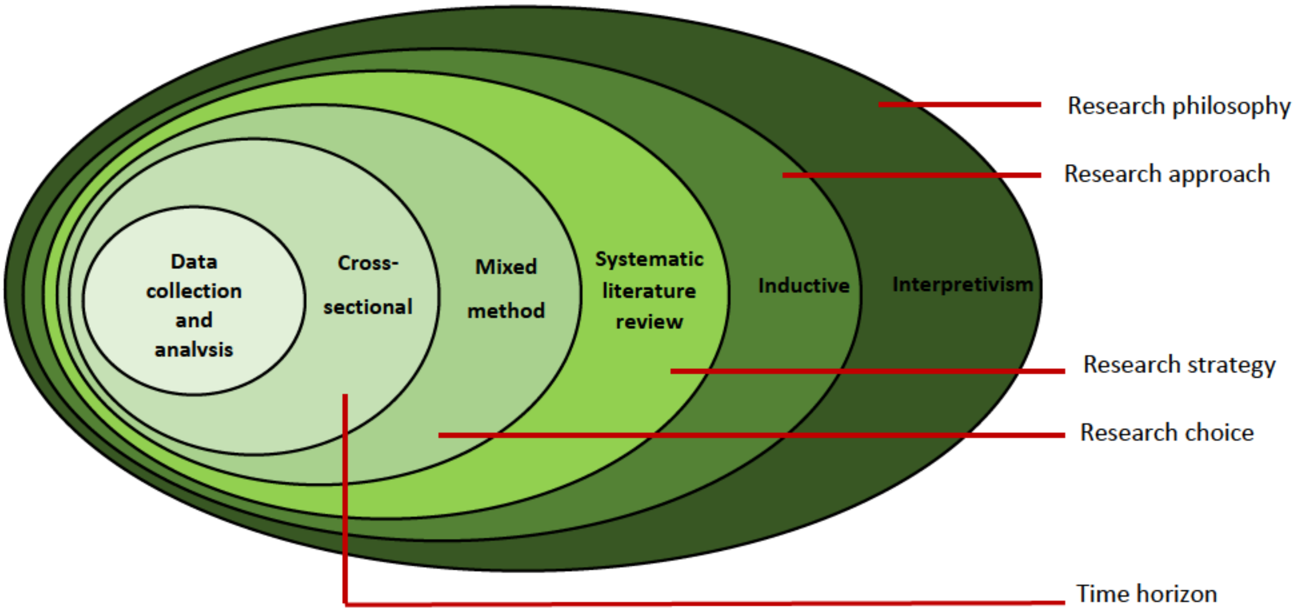
While longitudinal approaches show changes over time, the cross-sectional approach best meets the objectives of the systematic review for a focused assessment of the recent literature (Liberati et al., 2009). It is thus considered the best choice in the summaries of existing findings and emerging themes that reflect recent advances in blockchain technology without extended periods of time generally needed for trend analysis (Petticrew & Roberts, 2006).

3.2 Saunder's Research Onion Model Developed

Figure 1 portrays the graphical representation of the research design which conforms to the Saunder's research onion model created by the researcher based on the above identification of each layer.

Figure 1

Saunders's Research onion



Note: Author constructed *(2024)*

3.3 Data Collection Method

3.3.1 Search Criteria

The search criteria are developed for this review to ensure that the literature collection on blockchain technology in P2P energy trading is comprehensive and focused. The eligibility parameters are described as follows.

The following table (Table 1) shows the search criteria implemented in the study.

Table 1

Search criteria

Search Criteria	Eligibility Parameters	
Databases	Scopus	
Evidence criteria	Peer reviewed academic journal articles	
Key words	Blockchain Block chain Distributed ledger technology Cryptocurrency Crypto currency	Smart contracts Consensus mechanisms Peer-to-peer P2P Energy trading Energy exchange
Search within	Article title, abstract, keywords	
Language	The research focused only on English-language articles	
Time period covered	The research articles published throughout the time frame of 2014 to 2024.	

Note: Author constructed (2024)

Since Scopus hosts a large collection of peer-reviewed literature across various disciplines, it is targeted as the primary database. Scopus presents peer-reviewed journals that are more reliable, and the search criteria were developed to grasp the most relevant papers. To reduce the biases in database indexing, several keywords ("blockchain," "P2P energy trading," "smart contracts") and their variants ("block chain," "crypto currency") were used to make sure that even the articles tagged differently were included. Moreover, Bibliometric Analysis was used for crosschecking.

This key emphasis on peer-reviewed academic journal articles ensures that the literature included represents credible material that has been strongly evaluated by experts within the particular field, which enhances any findings and conclusion arrived at through the review.

These keywords are additive from the various relevant terms related to blockchain technology in general, and its application in energy trading. The inclusion of variants such as "blockchain" and "block chain" helps in capturing a wide scope of literature. This expansive keyword approach allows for not missing critical studies and permits a nuanced development of the topic. The main focus of the review is to investigate blockchain technology's role and functionality in energy trading. Incorporating terms such as "environmental impact" as key words on their own might dilute the focus of the search strategy toward sustainability and ecological matters, which are not the major focus of this study. However, the economic and environmental factors related to energy trading are intrinsic in the selected literature, extracted through the use of the major keywords "Blockchain" and "Energy Trading." By targeting these broad, central terms, the review ensures that studies addressing relevant factors, such as the economic viability and environmental implications of blockchain, are naturally embedded within the literature.

Focusing the search on article title, abstract, and keywords maximizes the relevance of the literature retrieved. This will ensure that only articles on core themes related directly to the study in question are considered, filtering out irrelevant studies.

Limiting the research to English-language articles, on one hand, has been a practical point of accessibility, but on the other hand, it allowed the inclusion of key global discussions and emerging trends in blockchain's role in P2P energy trading in this review (Petticrew & Roberts, 2006).The approach that excludes non-English sources will miss some regional insights but guarantees that the literature synthesized is accessible to a wide audience, peer-reviewed, and representative of prominent research in the subject area. This selection criterion will ensure coherence and relevance within the review, as findings can be presented within a manageable scope with broad applicability (Moher et al., 2015).

The period 2014 to 2024 is selected because it encompasses the latest development and research in changing blockchain technology so fast within the last ten years. On the other hand, this is the period during which scholarly interest in blockchain surmounted a tipping point of significance, starting from 2014. This allows the major development of blockchain and energy trading to fall within this period and hence set a timely context for review.

3.3.2 Defining Inclusion and Exclusion Criteria

The inclusion and exclusion criterion helped in filtering of the articles that would be taken through the systematic review, thus ensuring that only the most focused, relevant and high-quality results are produced.

The selected criteria for this specific research are elaborated in the following Table 2.

Table 2

Inclusion and exclusion criteria

	Inclusion Criteria	Exclusion Criteria	
Time	• 2014-2024	• All the other years	
Subject area	• Computer Science • Energy	• Dentistry • Veterinary • Nursing • Health Professions • Psychology • Arts and Humanities • Immunology and Microbiology	• Pharmacology, Toxicology, and Pharmaceutics • Neuroscience • Agricultural and Biological Sciences • Chemical Engineering • Biochemistry, Genetics, and Molecular Biology • Chemistry
Document type	• Article	• Erratum • Short survey • Editorial • Note • Retracted • Data paper	• Letter • Conference paper • Conference review • Book chapter • Review • Book
Language	• English	• Chinese • German • Russian • Spanish • Japanese • Italian • Undefined	• Korean • Turkish • Persian • Ukrainian • Novegian • French
Source	• Journal	• Trade journal	

		• Conference proceeding
Publication stage	• Final	• Article in press

Note: Author constructed (2024)

The publications from 2014 to 2024 were considered so that the recent changes in blockchain technology and its implementation in P2P energy trading could be identified. This period can be marked as one of the eras of growth for both fields and is thus crucial for the study.

Focusing on Computer Science and Energy ensures that the selected literature directly addresses the intersection of blockchain technology and energy trading, aligning with the review's objectives Fields, such as dentistry or psychology, are excluded to avoid dilution of focus, because those fields are not likely to contribute to the core technical and operational issues of blockchain in energy markets. Interdisciplinary areas, such as Environmental Science or Economics, which might also be relevant to the topic, are omitted with the aim of not losing coherence with the technological and energy-based axis of this review. This is due to the fact that their inclusion may extend the scope widely and introduce other frameworks that might turn the review more difficult to analyse. The economic factors are implicitly included in some of the selected papers that overlap the technological and operational perspectives of blockchain implementation in energy markets. This ensures that the economic aspects are considered without widening the scope unnecessarily by the inclusion of more keywords or unrelated frameworks.

The exclusion of non-peer-reviewed articles ensures the literature has passed through critical review, enhancing reliability and validity. Exclusion of document types such as editorials or reviews excludes biases and thus ensures data is derived from original research.

The choice of materials from reputable journals ascertains that academic integrity in terms of the credibility and reliability of the studies represented is ensured. Exclusion of sources like trade journals helps maintain the focus on scholarly work.

The selection of only the finally published articles adds to the integrity of the study in terms of making sure that the data represented is complete and authoritative. The exclusion of articles still in press ensures one does not rely on incomplete or unpublished findings.

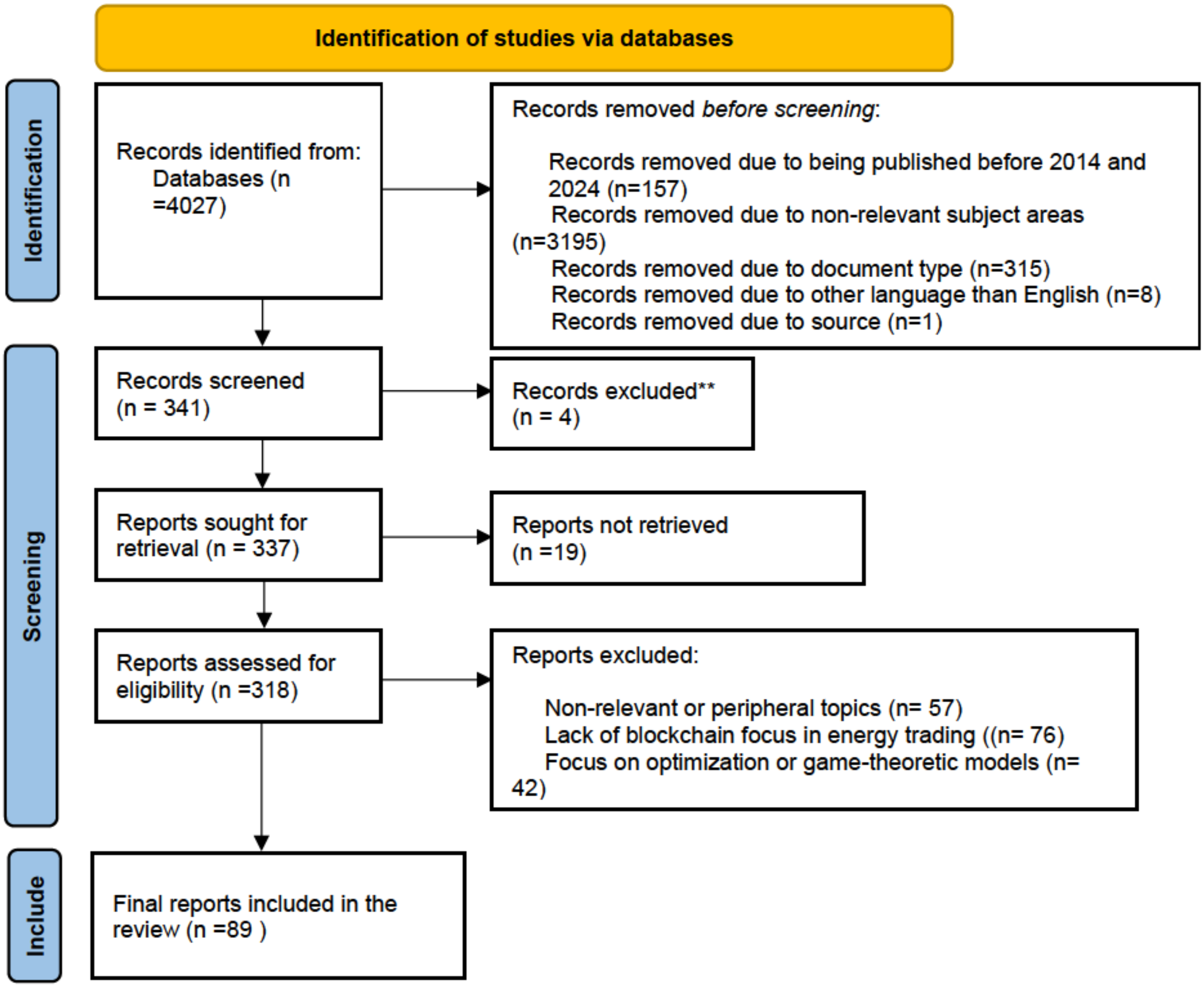
3.3.3 Screening and Selection Process

Screening and selection are pivotal components of the systematic literature review, whereby only highly relevant and high-quality studies are included. Selection in this process follows a structured approach given by the PRISMA guideline, standardizing how to report systematic reviews and meta-analyses.

The Figure 2 depicts the PRISMA flow diagram the researcher followed in the study while deciding the number and the type of relevant research papers.

Figure 2

PRISMA flow diagram



Note: Author constructed (2024)

The preliminary step of identification included an advanced search on Scopus. It yielded a total of 4,027 records about blockchain technology and P2P energy trading. During the screening phase, the exclusion criteria were then applied in terms of relevance to the research topic, language other than English, and irrelevant areas like Computer Science and Energy. A total of 341 records passed through this filter. Following this, a check for duplication yielded the exclusion of 4 duplicate records. The rest were checked for retrievability, which excluded 19 studies that were irretrievable. With the application of these criteria, a final eligibility check was made on 318 records in reviewing relevance and with respect to the scope of the research. This led to the final selection of 89 research journals whose content would be analysed.

3.4 Data Analysis

In this study, both quantitative bibliometric analysis and qualitative synthesis were combined in the approach to analysing the data for an integrated understanding of the literature following a mixed method approach. Bibliometric analysis is a quantitative approach that underpins the study of publication trends, author productivity, citation patterns, among others, which helped the structured understanding of development in the field. Key metrics considered while performing the bibliometric analysis included citation count, H-index value, co-authorship network, amongst others.

Tableau has been used as the prime visualization tool to generate detailed graphs, plots, and maps for visual representation of the complex relationships of the dataset. This further allows enhancing clarity and the accessibility of the findings through clear visualization of trends, key topics, and geographic distributions.

The blend of bibliometric and visual analysis enabled the ascertaining of thematic patterns and research gaps, which was in tune with the objectives of the study. Such a mixed-method approach has, therefore, been invaluable for deep excavation in the literature on blockchain and P2P energy trading.

3.5 Ethics and Limitations

3.5.1 Ethical Issues

A systematic literature review must be performed with strict adherence to ethical principles to maintain research integrity and ensure the credibility of the findings. Ethical issues that would be addressed in this study include the following:

The results and interpretations from the literature reviewed are reported honestly, with integrity based on good ethical standards in reporting research. Methods, results, and conclusions are represented correctly and without misinterpretation or selective reporting. Special care is taken with studies involving human subjects, respecting confidentiality and data privacy, especially in blockchain research where sensitive user data is so crucial. Additionally, studies involving proprietary blockchain technologies are handled cautiously to prevent disclosure of confidential information, ensuring the original research's integrity. These measures strengthen the credibility and reliability of this study's findings.

All citations of literature reviewed are done appropriately to give credit to the original authors and to avoid plagiarism. It is important to make sure other people's work is well respected and contributions recognized.

Study selection in this review is done on predefined criteria to minimize any selection bias. A systematic approach is followed whereby objective screening and selection ensured that the review reflected a comprehensive, unbiased look at available literature.

Since this study is based on publicly available academic literature, no direct concerns about personal data or confidentiality have been raised; however, ethical concerns persist with the use of data from studies that are derived from human subjects, putting the emphasis on ethics within primary research.

3.5.2 Research Limitations

The study entails several limitations that might affect the findings and generalization. The review covers studies between the years 2014 and 2024. It may exclude relevant studies that are out of this period. While this captures very recent works within these times, the foundational works that may offer important contexts or insights into how such a field evolved might be left out.

These selection criteria have specifically targeted studies of Computer Science and Energy, which may exclude highly relevant insights that can be found in interdisciplinary areas like economics, sociology, and environmental sciences. It could offer a set of new insights into the economic implications of blockchain, user behaviour, and its environmental impact within P2P energy trading. However, to retain focused scope and a dataset of manageable size, disciplines such as those mentioned above are excluded, possibly at the cost of breadth in insights.

It also points out publication bias, where studies that show significant or positive results get accepted into publications more often than those reporting null or negative findings. In so doing, publication bias may alter the apparent effectiveness or impact of blockchain technology in P2P energy trading by overrepresenting positive outcomes, hence the possibility of influencing the conclusions of the study towards a more favourable view of blockchain applications within energy markets.

Chapter 04
Results and Discussion

4.1 Descriptive Findings

The descriptive findings section presents the systematic findings of the research done using Bibliometrix and Tableau. They are presented as tables, graphs and maps and they reflect the variation and evolution of the literature on blockchain-related energy trading.

4.1.1 Completeness of Metadata

Figure 3 provides a summary of the completeness of metadata for 89 documents retrieved from the Scopus database.

Figure 3

Completeness of metadata

Metadata	Description	Missing Counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
C1	Affiliation	0	0.00	Excellent
AU	Author	0	0.00	Excellent
CR	Cited References	0	0.00	Excellent
DI	DOI	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
ID	Keywords Plus	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
RP	Corresponding Author	2	2.25	Good
DE	Keywords	6	6.74	Good
WC	Science Categories	89	100.00	Completely missing

Note: Bibliometrix (2024)

The table shows that most metadata categories, such as abstract (AB), affiliation (C1), author (AU), and cited references (CR), have no missing data, marked as "*Excellent"* in status. Key metadata like document type (DT), publication year (PY), and title (TI) are fully available, ensuring robust data for analysis.

However, there are some missing entries in the "*Corresponding Author*" (RP) and "*Keywords*" (DE) categories, with 2.25% and 6.74% missing data, respectively, marked as "*Good.*" Notably, the "*Science Categories*" (WC) metadata is completely missing (100%), marked as "*Completely missing.*" The lack of science categories may limit the scope for disciplinary comparisons in this research, though other metadata completeness ensures that the bulk of the analysis can proceed without significant gaps in bibliometric details.

4.1.2 Main Information

Figure 4 gives an overview of the major bibliometric features for the 89 documents published from 2016 through 2024.

Figure 4

Main Information

Note: Bibliometrix (2024)

This database shows works of a total of 354 authors, at an average of 4.55 co-authors per document. Single-authored is 1 document, and international co-authorship reaches 39.33%, indicating that the participation of researchers in blockchain-based P2P energy trading is highly collaborative internationally.

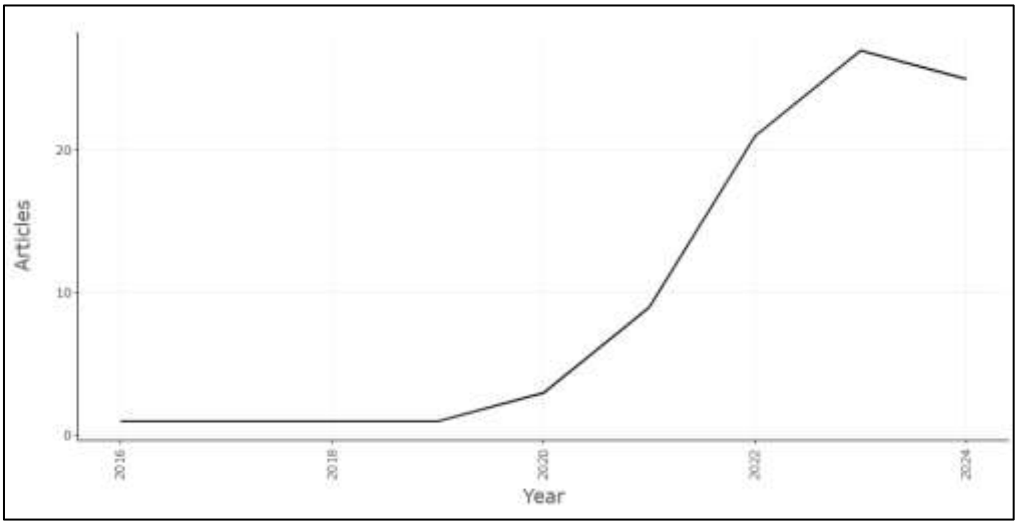
The documents came from 26 different sources, with a notable annual growth rate of 49.53%, reflecting the increasing academic interest in this field. The dataset included a total of 3,366 references and 298 keywords, which provide a strong foundation for keyword analysis and citation trends. On average, every document had 26.65 citations, which showed the scholarly impact of these publications. Meanwhile, the average age of the documents in this dataset was 1.51 years, showing the timeliness of the research in the evolving blockchain and energy sector.

4.1.3 Analysing Annual Scientific Production

Figure 5 shows the annual scientific production of publications related to blockchain-based P2P energy trading from 2016 to 2024.

Figure 5

Annual scientific production of publications related to blockchain-based P2P energy trading from 2016 to 2024



Note: Bibliometrix (2024)

Starting around the year 2020, the graph increases rapidly with a peak in 2022 where more than 20 articles have been published. The rapid growth in research output between 2020 and 2022 evidences the increase in interest regarding the application of blockchains for energy trading due to improved decentralized technologies and environmental concerns.

This trend is corroborated by the findings from similar analyses done by Zhang et al. (2022), and Xu et al. (2024), who experienced similar spikes in research on blockchain-related energy during this period, proving how well the field addresses current technological and environmental priorities. Zhang et al. (2022) further indicated that peak years in publications coincided with the key development of energy regulations and increasing government incentives for decentralized energy solutions, which therefore may indicate that policy developments probably fuelled academic interest. Xu et al. (2024), using data from Web of Science, also identified a peak in publications, although they noted a higher concentration of such publications came from Europe and North America, hinting at regional variation in research focus.

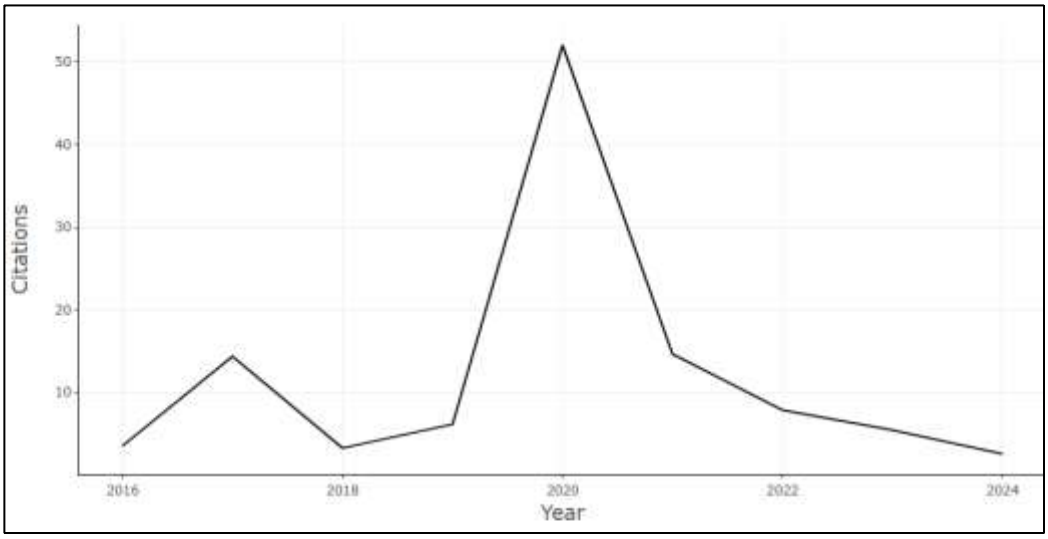
Before the year 2020, the research activity in this field was minimal, indicating that this area of study seems to have been lately identified as a significant thrust area of both academic and practical importance. The slight dip in 2024 might hint at stabilization in the rate of new publications, with the field continuing to attract research. The above trend depicts the rapid growth in this field due to various technological advances and emerging needs in the energy market.

4.1.4 Analysing Average Citations Per Year

Figure 6 presents the average number of citations per year of the research.

Figure 6

Average citations per year of publications related to blockchain-based P2P energy trading from 2016 to 2024



Note: Bibliometrix (2024)

There is a major spike in citations in the year 2020, where the average number of citations crossed 50. This depicts a sudden rise, hence inferring that some fundamental works around this time gained substantial academic attention and shaped the discourse on blockchain in energy markets. This can be supported by Zhang et al. (2022), whose research mentions that 2020 is a watersheds year due to the publication of two influential papers in that year regarding the most critical technological and regulatory issues in blockchain energy system

However, after 2020, there is a marked decline in average citations per year. Such a trend might be the result of a natural lag in the accumulation of citations for newer research, as suggested by Xu et al. (2024), using Web of Science data to indicate similar citation patterns while analyzing blockchain literature. Their results show that landmark works are often highly cited early on but then decline as the area polarizes and new work starts to focus on a number of subtopics which have emerged in the area.

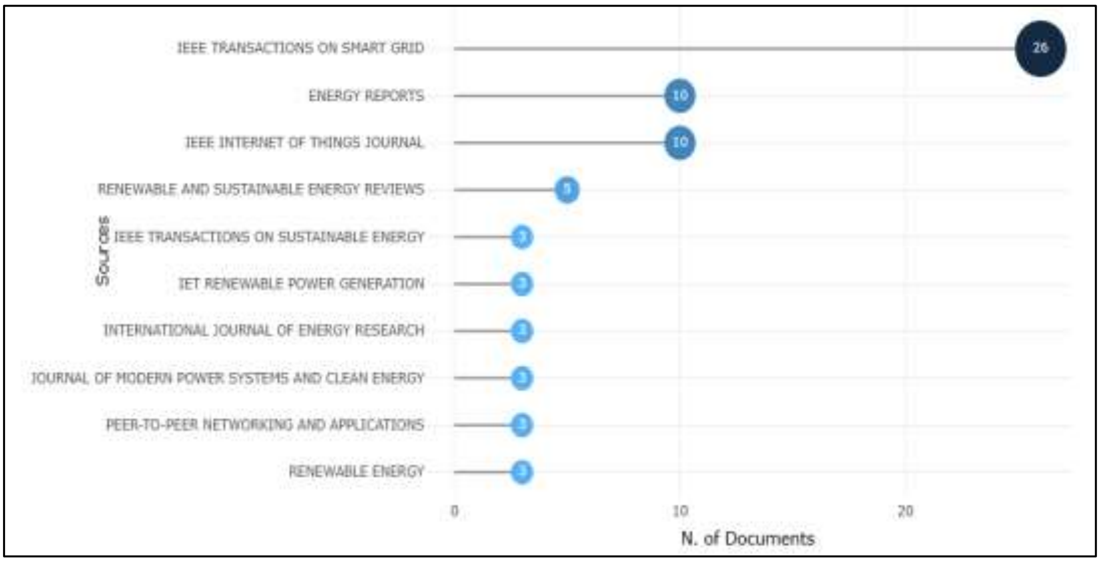
Moreover, Silvestre et al. (2020) go further to suppose that the drop could also indicate some change in research priorities or even a saturation in foundational topics: as academic interest broadens towards novelty in the aspects of blockchain, interoperability, privacy, and scalability in P2P trading contexts.

4.1.5 Analysing Most Relevant Sources

Figure 7 displays the leading publication sources for blockchain and P2P energy trading research.

Figure 7

Most relevant sources for blockchain and P2P energy trading research publications.



Note: Bibliometrix (2024)

As per Figure 7, *IEEE Transactions on Smart Grid* with 26 articles stands out as the leading publication source for blockchain and P2P energy trading research, underscoring its central role in this domain. Comparative studies such as Andoni et al. (2019) and Xu et al. (2024) confirm the leading role of IEEE in blockchain energy-related research, especially within high-impact technology classes. In particular, *Energy Reports* and *IEEE Internet of*

Things Journal contribute with 10 articles each, while *Renewable and Sustainable Energy Reviews* follows with 5 publications, showing the persistence of interest on this level. Other sources contribute with three articles, such as *IET Renewable Power Generation* and *P2P Networking and Applications*, further deepening the area, reinforcing together the interdisciplinary nature of blockchain research in energy systems.

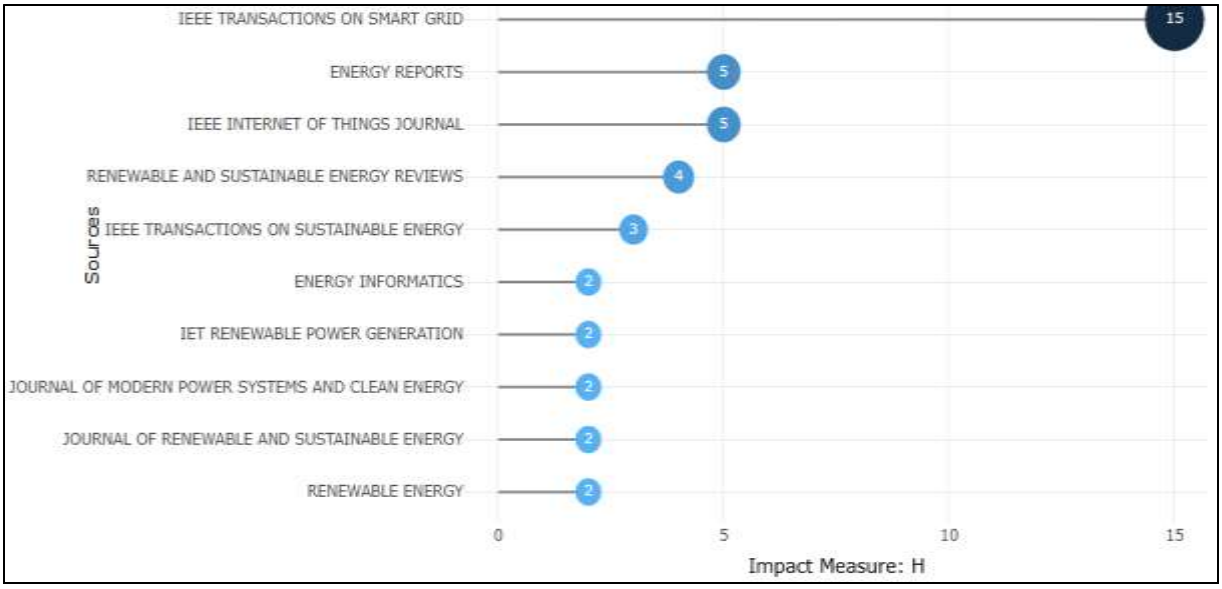
While *IEEE Transactions on Smart Grid* and other journals have contributed significantly to the literature related to blockchain applications in energy systems, limited attempts have been made to discuss in detail the interdisciplinary perspective that brings energy technology together with social sciences, economics, and regulatory studies. Future research may be directed at investigating blockchain's impact on energy policy development and consumer response to address the socio-economic implications of decentralized energy systems.

4.1.6 Analysing Sources' Local Impact

Figure 8 shows the local impact of key journals.

Figure 8

Local impact of key sources



Note: Bibliometrix (2024)

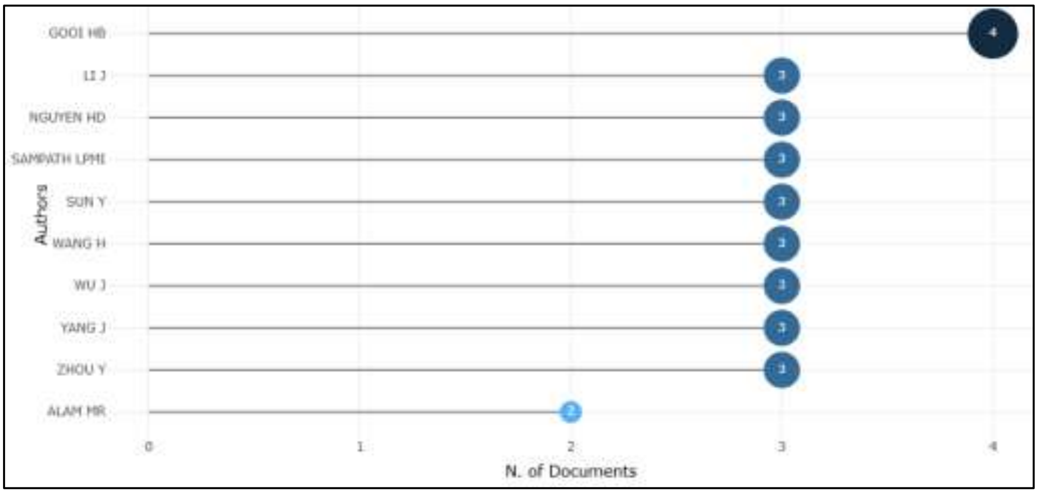
The *IEEE Transactions on Smart Grid* ranks highest with an H-index of 15, indicating its substantial influence in the field. Following closely are *Energy Reports* and *IEEE Internet of Things Journal*, both with an H-index of 5. Other high-factor contributing journals such as *Renewable and Sustainable Energy Reviews* and *IEEE Transactions on Sustainable Energy* find a place within the top contributing sources to the academic discourses of blockchain applications in energy markets.

4.1.7 Analysing Most Relevant Authors

The figure 9 presents the most relevant authors contributing to research on blockchain-based P2P energy trading

Figure 9

Most relevant authors contributing to research on blockchain-based P2P energy trading



Note: Bibliometrix (2024)

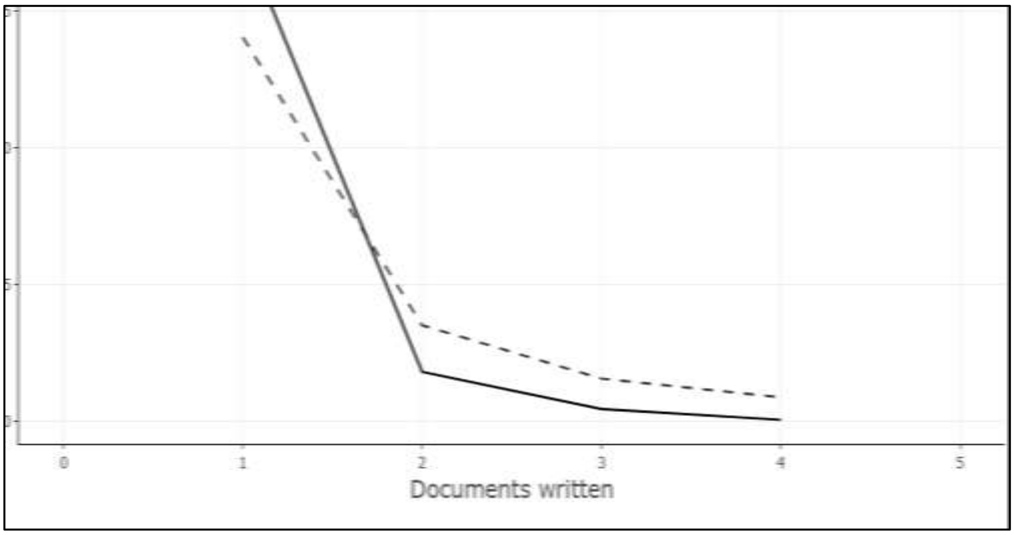
Gooil HB leads with four documents, reflecting significant contributions to the field, particularly in smart grid technology and blockchain integration. Authors such as *Li J*, *Nguyen HD*, *Sun Y*, and *Wang H* follow closely with three documents each, indicating their influence on the research landscape in decentralized energy systems. These researchers have focused on everything, from how blockchain enables better energy efficiency and security to enabling more sustainable energy trading. The concentration of contributions by these authors aligns with broader trends in blockchain research, as noted by Andoni et al. (2019), where thought leaders drive both the theoretical and applied advances in energy trading.

4.1.8 Analysing Author Productivity through Lotka's Law

Figure 10 presents author productivity in the considered research field, analyzed using Lotka's Law. Lotka's Law suggests that a small percentage of authors contribute a large number of documents, while the majority produce only a few (Lotka, 1926).

Figure 10

Author productivity through Lotka's Law



Note: Bibliometrix (2024)

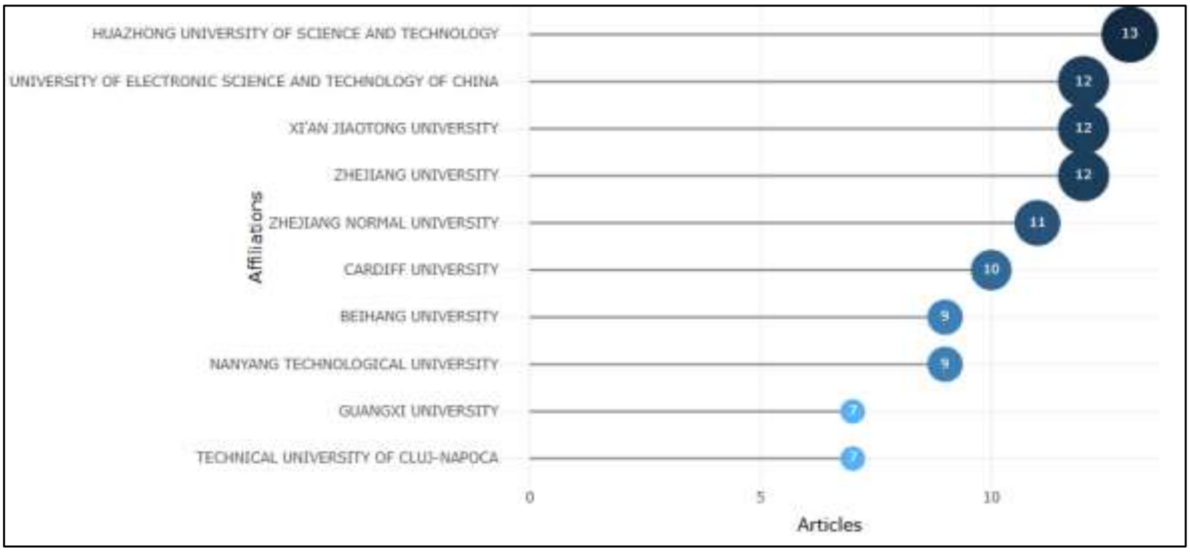
The graph indicates that over 75% of the authors in this dataset have written only one document, while a very small number have contributed two or more papers. The above observation is in conformance with Lotka's Law and shows the normal reverse relation between the number of authors and the number of documents produced by them. It brings out the distribution that a small number of prolific researchers drive the bulk of publications from a large pool of authors who would contribute research periodically.

4.1.9 Analysing Most Relevant Affiliations

Figure 11 displays the most relevant affiliations revealed in the study.

Figure 11

Most relevant affiliations revealed in the study



Note: Bibliometrix (2024*)*

As per the results, *Huazhong University of Science and Technology* leads with 13 articles, followed closely by the *University of Electronic Science and Technology of China*, *Xi'an Jiaotong University*, and *Zhejiang University*, each contributing 12 articles. This is further evidenced in the work of Gawusu et al. (2024), who also showed high contributions by the Chinese and European institutions concerning blockchain and decentralized energy studies and, hence, their regional research priorities are essentially shaped through the breadth of government funding and academic initiatives.

Other notable institutions include *Zhejiang Normal University* with 11 articles and *Cardiff University* with 10 articles. These affiliations highlight the dominance of Chinese universities in the research landscape of blockchain applications in energy trading. International collaboration and diverse geographic contributions are shown by the inclusion of European institutions such as *Cardiff University* and *Technical University of Cluj-Napoca*.

This distribution underlines the interest of international academia in using blockchain technology with energy systems and the role of the mentioned institutions in moving this new field.

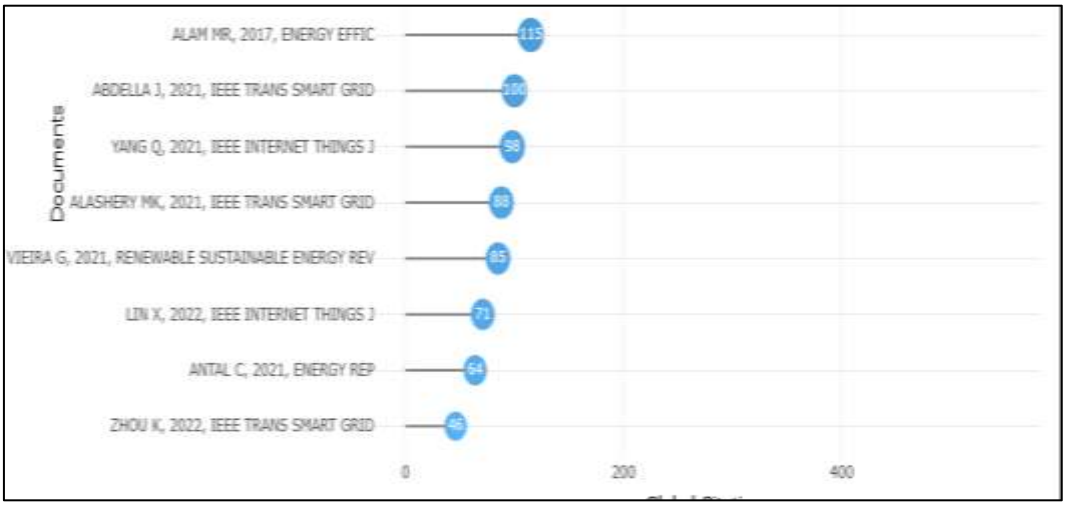
The regional emphasis of blockchain research emanating from Chinese and European institutions in energy trading indeed reflects the differing policy and funding landscapes. In this regard, Chinese universities have been at the forefront, with heavy governmental funding; for instance, Huazhong University of Science and Technology is leading in blockchain research in line with national strategies such as "Made in China 2025" that has accentuated swift technological deployment toward scalable applications in supporting energy security (Atkinson, 2024). This, in turn, will benefit European institutions like Cardiff University in their EU initiatives, such as the European Green Deal, in promoting an interdisciplinary collaboration approach in policy, regulatory, and environmental perspectives as highlighted by Xu et al. (2024). This, therefore, gives a wider approach in methodology that balances technological innovation with sustainability goals. Such differences also indicate how local policy and strategic priorities are influential in shaping their academic research; whereas China focuses on rapid progress, Europe emphasizes compliance and long-term sustainability (Silvestre et al., 2020).

4.1.10 Analysing Most Global Cited Documents

Figure 12 presents the top globally cited documents identified in the study.

Figure 12

Most globally cited documents identified in the study



Note: Bibliometrix (2024)

Leading the list is *Tushar W. (2020)* from *IEEE Transactions on Smart Grid* with 555 citations, highlighting its significant impact on the field. Following this is *Zhang Z. (2020)* with 186 citations, and *Alam MR. (2017)* from *Energy Efficiency*, which has received 115 citations.

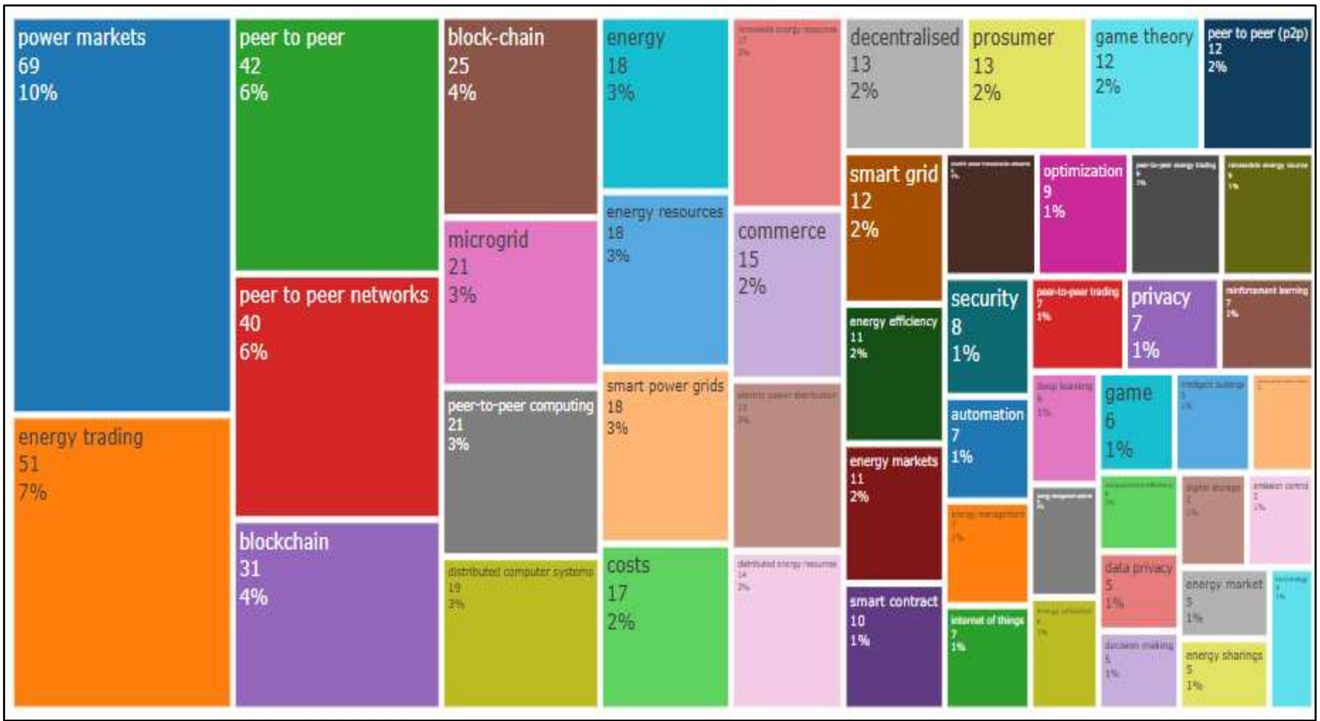
Other highly cited works include *Abdella J. (2021)* and *Yang Q. (2021)*, which were published in *IEEE Transactions on Smart Grid* and *IEEE Internet of Things Journal*, respectively. These highly-cited articles provide insights into the foundational role of blockchain in increasing efficiency, security, and scalability within energy markets. Citation data underlines the impact of these two publications in the development of blockchain applications for decentralized energy trading and also that early influential research is still relevant.

4.1.11 Analysing the Most Frequent Words

Figure 13 presents a tree map that visualizes the most frequent keywords in blockchain-based P2P energy trading research.

Figure 13

Most frequent keywords in blockchain-based P2P energy trading research



Note: Bibliometrix (2024)

The research landscape about the use of blockchain in energy systems is dominated by the topics *"power markets"* with 10%, followed by *"energy trading"* with 7%. Other significant keywords are *"peer-to-peer networks"* at 6%, *"blockchain"* itself at 4%, and "*microgrid"* with 3%, while there is a clear focus on technical and market-driven aspects of blockchain applications in energy systems. The smaller ones, but very relevant, are *"privacy*," *"security,"* and *"smart grids,"* dealing with secure and scalable solutions for decentralized energy markets. This visualization shows a number of research themes that continue to shape this ever-evolving field.

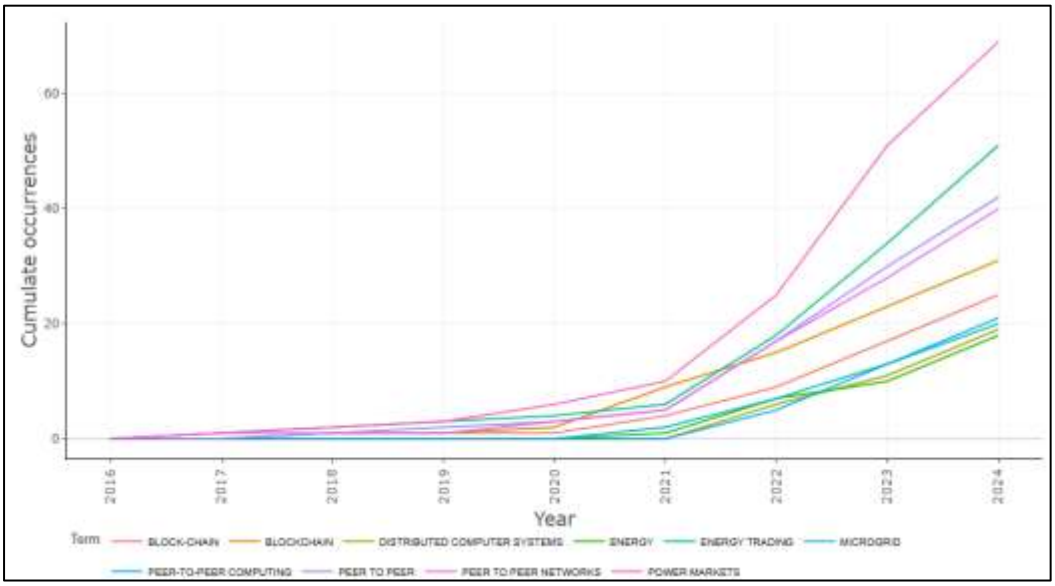
The emphasis on terms around *"energy trading"* and *"smart contracts"* underlines preoccupation with transaction efficiency and automation. However, limited research has delved into the ethical implications of blockchain's data transparency in energy trading. Future research should consider models balancing transparency with user privacy in the context of sensitive data in decentralized market transactions.

4.1.12 Analysing Words' Frequency over Time

Figure 14 is an illustration of the cumulative occurrences of key terms in blockchain-based P2P energy trading research from 2016 to 2024.

Figure 14

Words' frequency over time in blockchain-based P2P energy trading research from 2016 to 2024



Note: Bibliometrix (2024)

The term *"blockchain"* (in its hyphenated and non-hyphenated forms) shows a sharp increase in frequency starting in 2020, highlighting the growing interest in its application to energy systems. Other keywords are *"energy trading"*, *"peer-to-peer networks"*, and "*power markets"*, which also represent strong upward trends, reflecting the emerging academic focus on decentralized energy systems. *"microgrid"* and *"distributed computer systems"* also show consistent growth, further emphasizing the technical underpinning of this research. The graph below illustrates the growth in scholarly attention that blockchain receives as one of the possible solutions for modernizing energy markets in order to allow for more efficient and transparent P2P energy trading.

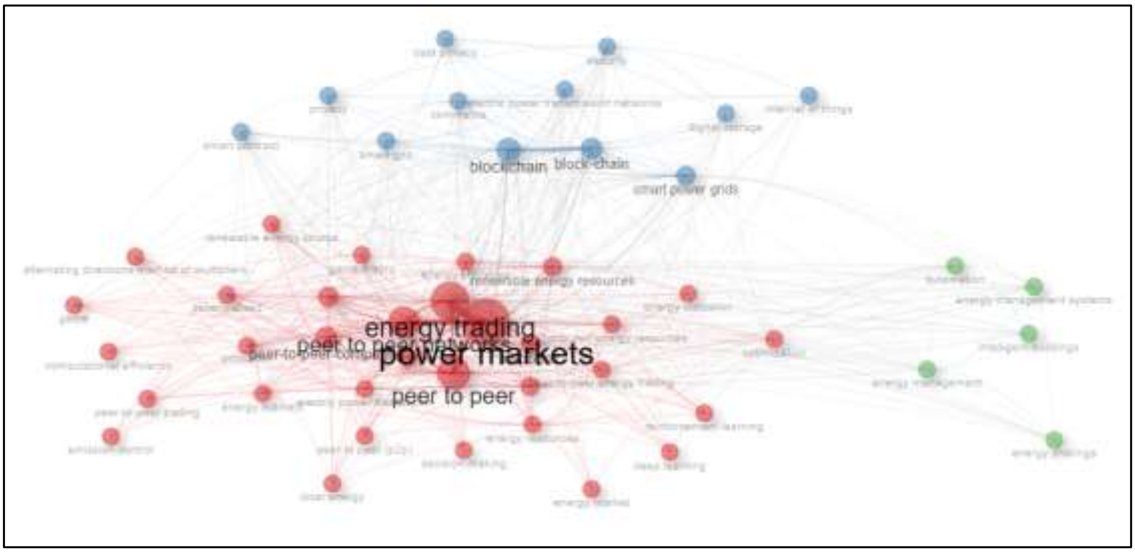
The growing frequency of terms like *"blockchain"* and *"energy trading"* suggests an intensifying interest in these areas. However, there is a lacuna in longitudinal studies that track the long-term impacts of blockchain on energy market dynamics. Longitudinal studies in the future should also consider how blockchain will affect energy efficiency, market stability, and cost-effectiveness with time.

4.1.13 Generating Co-occurrence Network

Figure 15 provides the co-occurrence network of key terms in the concentrated field.

Figure 15

Co-occurrence network of key terms



Note: Bibliometrix (2024)

The use of the network analysis of co-occurring terms is justified by the fact that this method is particularly fitted to showing which are the links between terms and concepts, thus offering a visual view of the themes that appear more frequently in conjunction and their relative weight in the literature (Xu et al., 2024).

The largest nodes, such as *"power markets," "energy trading,"* and *"peer-to-peer,"* are central in the network, indicating their pivotal roles in this research area. These are closely linked to *"blockchain," "distributed energy resources,"* and *"smart power grids,"* reflecting the integration of technical innovations with energy market dynamics. It also underlines the clusters around *"privacy," "security,"* and *"smart contracts"* concerns related to data protection and secure transactions, crucial in a decentralized energy system. In turn, thematic clusters hint at the core issues of *"energy management systems," "automation,"* and *"optimization"* regarding the field's focus on greater efficiency and scalability. This network provides insight into the key interrelated themes that shape blockchain applications to energy trading.

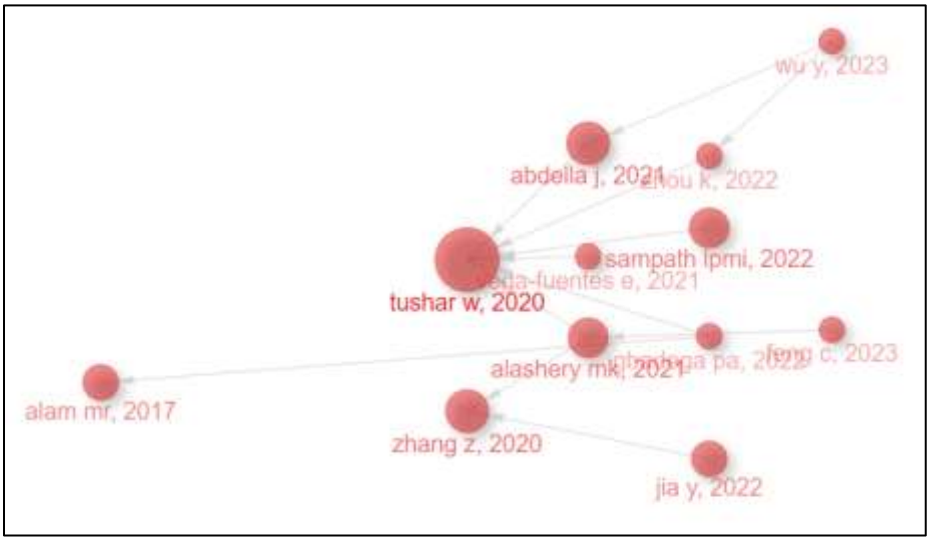
While the co-occurrence network reveals connections between major themes like *"power markets"* and *"peer-to-peer,"* there is limited research into how these components interact in regulatory contexts. Future work should seek to identify regulatory frameworks through which decentralized energy markets can coexist with national grid infrastructures, particularly in regions with restrictive regulatory environments.

4.1.14 Generating Historiograph

Figure 16 shows the historiograph of influential studies in blockchain-based P2P energy trading research.

Figure 16

Historiograph of influential studies in blockchain-based P2P energy trading research



Note: Bibliometrix (2024)

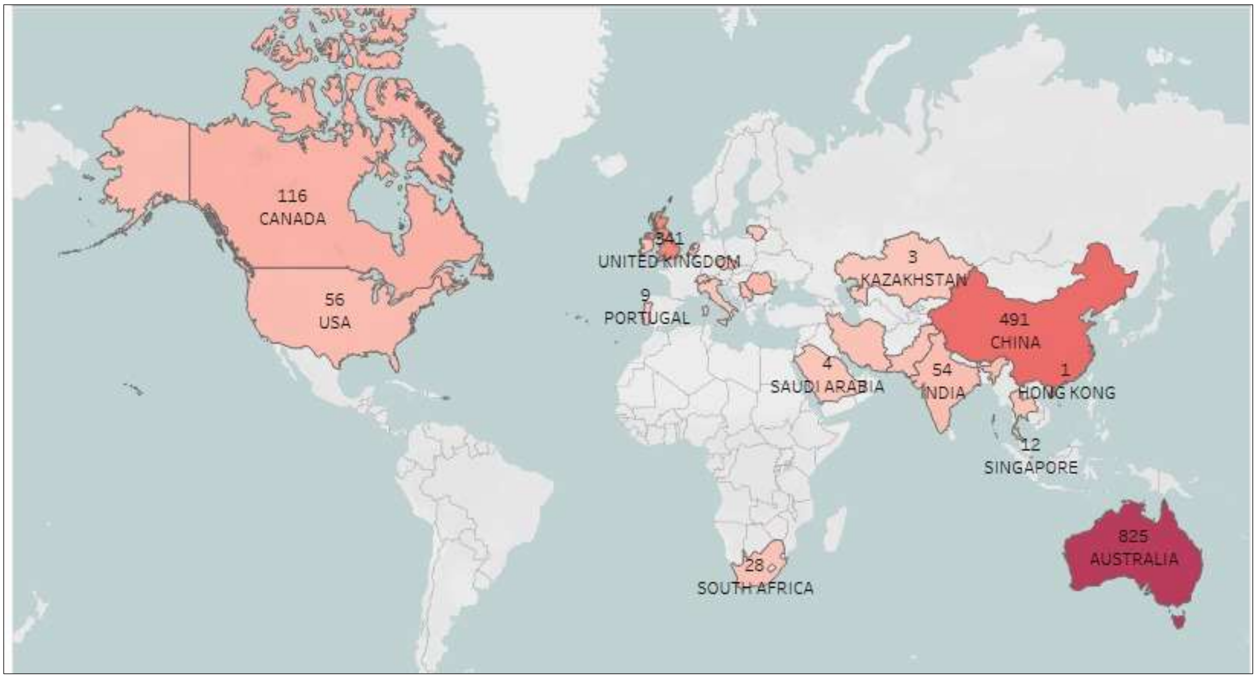
The central position of *Tushar W. (2020)* highlights its key role in shaping subsequent research, with multiple studies such as *Abdella J. (2021)* and *Alashery MK. (2022)* citing it. Other influential works, including *Alam MR. (2017)* and *Zhang Z. (2020),* also appear prominently, showing how they have contributed to the field's development. This historiograph provides a citation lineage that illustrates foundational studies leading to recent advances in blockchain applications for energy trading. The visualization emphasizes the chronological flow of knowledge and the interconnectedness of highly influential research in this domain.

4.1.15 Analysing the Most Cited Countries

Figure 17 displays the most cited countries in the concentrated field of study.

Figure 17

Most cited countries in the concentrated field of study



Note: Tableau (2024)

Australia leads significantly with 825 citations, followed by China with 491 citations, and Canada with 116 citations. Other notable contributors include the USA (56 citations) and South Africa (28 citations). High citation counts for these countries signify important contributions towards the advance of blockchain applications in energy trading, especially in aspects related to a decentralized ledger system and smart contract functionality. The international distribution of citations falls in line with global interests and perspectives pushing innovation and research in blockchain-enabled energy systems.

This global citation distribution reflects the widespread academic interest in blockchain-enabled energy systems, with each country bringing unique perspectives shaped by their specific technological and regulatory contexts. For instance, Xu et al. (2024)

identified that the high engagement in Australia is informed by strong government support for renewable energy, which is in line with the applications of blockchain for energy efficiency and sustainability. The high citation count for China testifies to the seriousness of the country in effectively using technology to render solutions for energy management, usually with big funding for smart grid and blockchain research.

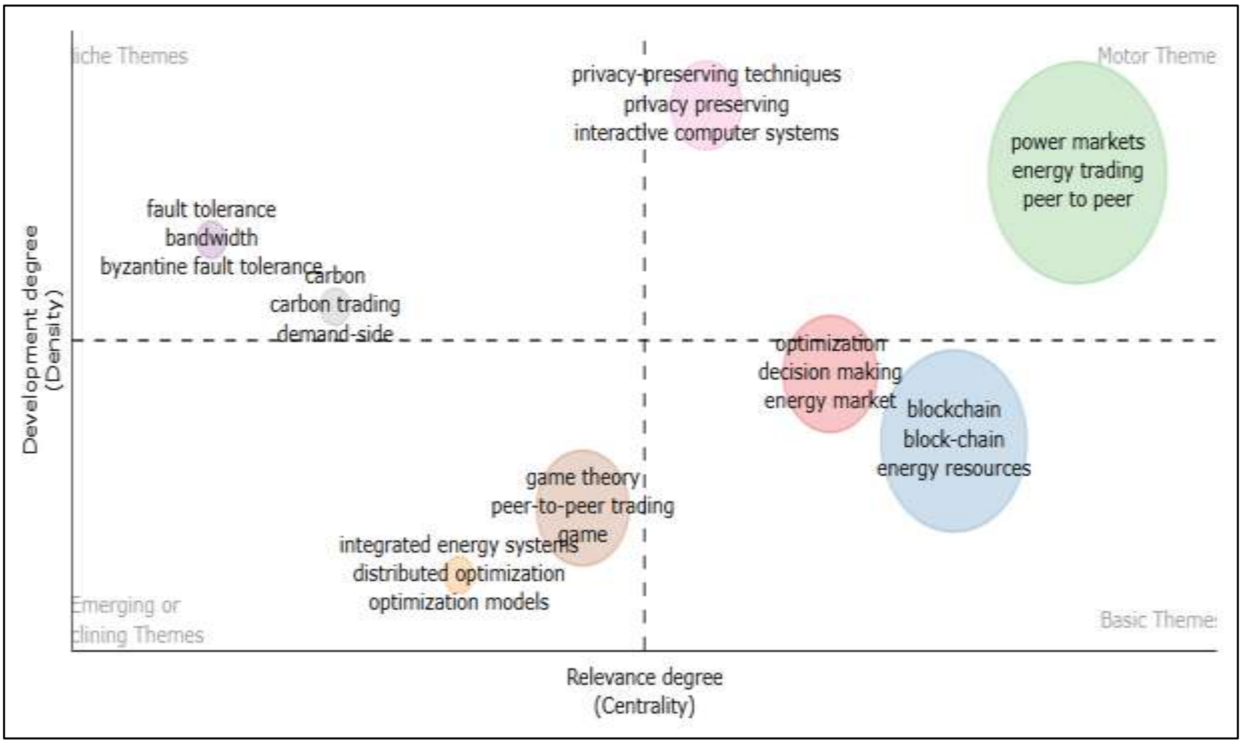
While these contributions highlight national expertise, a gap exists in cross-country comparative studies, which could offer valuable insights into how varied regulatory and cultural environments impact blockchain adoption in energy trading. According Karisma & Tehrani (2023), comparative analyses conducted in different regions could show various facilitators or barriers on the road to blockchain adoption and thus allow understanding the best practices and regulatory needs from every corner of the world. Such comparisons need to be taken into consideration by future research in the identification of pathways that would support the wider adoption of blockchain in decentralized energy markets.

4.2 Thematic Map

Figure 18 presents the thematic map of the systematic literature review, divided into four quadrants—Motor Themes, Basic Themes, Niche Themes, and Emerging or Declining Themes.

Figure 18

Thematic map



Note: Bibliometrix (2024)

The above map, based on co-word and thematic analysis, shows the visual structure of topics with regard to centrality and development density. This indicates whether or not the themes are foundational, well established, emerging, or niche. Thematic mapping was done on purpose, since it allows for a structured overview of existing research directions and gaps that will enable the identification of established and potential research areas in blockchain-based P2P energy trading (Cobo et al., 2011).

4.2.1 Motor Themes (High Centrality, High Density)

Motor themes are both highly relevant and well-developed, representing areas with strong research engagement and foundational significance. In this quadrant, power markets, energy trading, and P2P technologies appear as dominant motor themes. These terms further reiterate the decentralized energy market, where P2P energy trading can directly involve prosumers in energy exchange. It would not go without saying that the higher frequency of these themes stands for growth in attention towards less use of a centralized energy system, more transparency, and consumer power with the help of blockchain structure (Mengelkamp et al., 2018).

4.2.2 Basic Themes (High Centrality, Low Density)

Basic themes have high centrality but low development density, indicating their foundational status in the field but suggesting opportunities for further exploration. Key topics here include blockchain, block-chain, and energy resources. As fundamental elements in the application of blockchain for energy systems, these themes provide the essential building blocks for understanding how blockchain can be integrated to enhance energy resource management. Attributes of blockchain technology, such as transparency, immutability, and decentralization, may yield tremendous benefits to energy transaction optimization and protection of data privacy, an important attribute in the P2P energy markets (Yang et al., 2021). On the contrary, this quadrant features a low density, relating that although these are main topics, there could be unexplored elements that might increase knowledge on their practical aspect of implementation.

4.2.3 Niche Themes (Low Centrality, High Density)

Niche themes have high development density but low centrality, signifying specialized areas that, while highly researched, have limited relevance to broader themes in the field. Topics such as fault tolerance, bandwidth, BFT, and carbon trading fall within this quadrant. These deal with more specific technical themes challenging blockchain-based energy systems on their reliability, scalability, and resilience. Examples include fault tolerance and BFT, notions that deal with the ability of blockchains to maintain secure operations even in adversarial environments.

4.2.4 Emerging or Declining Themes (Low Centrality, Low Density)

Emerging or declining themes have low centrality with low development density, indicating a domain that is either coming up or losing significance. Specific topics showing up here include game theory, P2P trading, and distributed optimization, indicating further possible future directions or areas of waning interest. For instance, game theory has been used in modeling strategic interactions in decentralized energy trading for the optimization of pricing mechanisms and incentivization of energy production (Yao et al., 2024).

4.3 Literature Review Findings

RQ2: How do the decentralized ledger and smart contract functionalities of blockchain impact transaction efficiency in P2P energy trading?

Decentralized Ledger and Transaction Efficiency. Blockchain’s decentralized ledger is recognized for streamlining transactions in P2P energy trading by removing third-party intermediaries, such as utility companies traditionally responsible for transaction verification and processing (Piao et al., 2024). The transaction time and costs can be reduced by blockchain through the direct transaction among the prosumers. It is also in line with the goals of P2P trading: heightened efficiency and cost savings (Gao et al., 2024). A shared, immutable ledger adds to transparency and accessibility in the trustless setting of a decentralized energy market whereby participants can independently verify the transactions and builds trust in the system.

However, a critical unresolved contradiction in the literature lies in the trade-off between decentralization and scalability. Traditional consensus mechanisms like PoW, while secure, are computationally intensive and slow, making them less suitable for the real-time demands of energy trading. Other alternatives, such as PoS and Proof of Authority (PoA), assure faster processing and higher energy efficiency. PoS, for instance, can centralize power by favoring entities with greater resources, potentially undermining blockchain's decentralized nature (Ye et al., 2024). Similarly, PoA relies on trusted authorities, which could compromise security in energy markets (Devi et al., 2023).

These have steered awareness to hybrid and permissioned models of blockchain, which balance operation scalability against decentralization. Such benefits are for example, permissioned networks for instance can benefit from efficiencies attainable through permissioned networks while only choosing to be transparent to important stakeholders. However, Zhang et al. (2020) noted that, such models would defeat the entire purpose of the decentralization offered by blockchain, and as such, some aspects of centralized control would reemerge. This current debate once again emphasizes the importance of research for the next generation consensus algorithms that will make the technology scalable without sacrificing decentralization, transparency or security.

Smart Contracts and Transaction Efficiency. Smart contracts which are programmed to execute themselves once certain conditions occur, are generally regarded as disruptive in energy trading. Through incorporation of contract automation, they remove middlemen, this cuts on cost since less paperwork is done and decreases chances of errors. Smart contracts as pointed by Zhang et al. (2020) increase transaction throughput as they facilitate the rapid and effective trading environment. Alam et al. (2017) claimed that they also support dynamic price control, where energy prices may change their prices in response to demand and supply in real-time— a vital requirement to make point to point balancing of resources.

Nonetheless, the introduction of smart contracts bears several problems. One of the major paradoxes in the literature is lack of regulatory certainty on the ability of cap and trade regimes to enforce these across jurisdictions making cross border energy trades tricky (Mishra et al., 2023). Abdella et al. (2021) point to the fact that smart contracts themselves as virtually legal tender, their lack of harmonized legal frameworks can be insufficiently reliable for high-stakes transactions and if there are disputes, there are likely to be differences in legal opinions.

Also, smart contracts rely heavily on flawless programming: even minor bugs may lead to unforeseen effects and thus create distrust in this system. In this respect, Abdella et al. (2021) advise thorough code audits. These, however increase the costs. Mishra et al. (2023) suggest standardized templates that reduce risks, at some cost in flexibility for sophisticated energy transactions. This trade-off between standardization for reliability and the flexibility needed for sophisticated applications remains an unresolved issue in the adoption of smart contracts.

Table 3 summarizes the solutions of blockchain for reviewing transaction speed, advantages, and limitations, while the sources have been used in the paper.

Table 3

Summary table of blockchains' impact on transaction efficiency

Aspect	Positive Impact on Efficiency	Limitations and Critical Perspectives	Citations
Decentralized Ledger	Direct transactions without intermediaries reduce costs.	Scalability issues with PoW; PoS raises centralization risks.	Piao et al. (2024); Gao et al. (2024); Zhang et al. (2020)
	Builds trust and transparency among unfamiliar participants.	Hybrid models might sacrifice decentralization benefits.	Ye et al. (2024); Devi et al. (2023)
Smart Contracts	Automates execution, reducing costs and processing errors.	Inconsistent enforceability across jurisdictions; costly audits required.	Zhang et al. (2020); Mishra et al. (2023)
	Enables dynamic pricing for supply-demand balancing.	Vulnerable to coding errors; standardized templates may reduce flexibility.	Alam et al. (2017); Abdella et al. (2021)

Note: Author constructed (2024)

RQ4: What specific challenges and issues are associated with integrating blockchain technology into energy trading systems?

Scalability and Transaction Throughput. Scalability remains a significant challenge in blockchain-based energy trading, with traditional consensus mechanisms PoW criticized for high resource consumption and limited transaction throughput (Ye et al., 2024). This limitation directly impacts the integration of blockchain into energy trading systems, as real-time transactions are a critical requirement for energy markets. However, some researchers believe that other types of consensus algorithms can be more effective such as PoS or BFT. These mechanisms, as noted by Ye et al. (2024), leads to energy saving and faster transaction time but Devi et al. (2023) argue that while these alternatives show promise, their effectiveness depends heavily on the size of the network and requires large-scale trials to confirm scalability. Future research should focus on trialing these mechanisms in real-world energy trading markets to evaluate their feasibility and performance. Meanwhile, Mishra et al. (2023) focus on hybrid consensus models which merge the PoS with delegated validation and are scalable in such a manner; yet, it may be too technically complicated, while initial costs can prohibit the majority of users.

Data Privacy and Security Risks. While blockchain's decentralized and immutable nature enhances data transparency, it introduces privacy challenges in energy trading. Piao et al. (2024) raise concerns that public blockchains may inadvertently expose consumer data, allowing behavioral patterns to be inferred, which could compromise user privacy. Advanced cryptographic solutions like zero-knowledge proofs are proposed to mitigate these issues, but Piao et al. (2024) argue that such techniques add computational complexity, impacting system performance.

On the other hand, Alam et al. (2017) has recommended the use of permissioned blockchain for energy trade. Permissioned blockchains will offer restricted access into the network and therefore offer superior privacy while enhancing the transparency of the chain. However, this strategy is not without criticism; Zhang et al., (2020) opined that permissioned meant decentralization was limited which leads to re-emergence of centralization pro-traits which are unhelpful for block chain. Future research could explore optimized cryptographic techniques or hybrid models that combine permissioned and public blockchains to balance decentralization and privacy.

Regulatory and Legal Uncertainty. The regulatory landscape for blockchain remains inconsistent across jurisdictions, creating challenges for energy trading implementation. The legal enforceability of smart contracts varies, with some regions recognizing them as binding while others do not, affecting cross-border energy transactions (Zhang et al., 2020). GDPR and similar regulations complicate data sharing on blockchains, restricting operational flexibility. Mishra et al. (2023) state that these challenges could be solved by creating standard regulatory norms, though the opponents argue that blockchain is incapable of standard regulation due to its nature. Future research could focus on developing adaptive regulatory frameworks that allow decentralized systems to comply with regional and international data-sharing laws. Devi et al. (2023) have proposed a variant in which sensitive information is maintained off-chain, but the metadata of the transaction is on-chain, thus trying to balance regulatory compliance and blockchain decentralized principles. While this sounds promising, it indeed brings up concerns regarding added operational complexity and potential latency in accessing the data kept off-chain.

High Energy Consumption and Environmental Concerns. High energy consumption of blockchain, particularly in PoW networks, contradicts the environmental considerations of renewable energy markets. According to Gao et al. (2024), the trading networks based on PoW might lead to an increasing carbon footprint, thus opposing sustainability. Mechanisms like PoS are greener, but Gao et al. (2024) mentioned that in most regions, the technical and regulatory obstacles have confined its adoption to some degree. Tushar et al. (2020) recommended the adoption of hybrid energy-efficient consensus mechanisms in trading energy resources, which may turn out to need high-scale and costly infrastructural overhauls. Zhang et al. (2020) recommend renewable energy-powered nodes to handle the energy consumption issue of blockchain; this would require an integrated and infrastructural change in implementation, which is one of the major barriers to integration. Further research can be done on the integration of renewable-powered nodes with consensus models that are energy-efficient.

Technical Complexity and Interoperability Issues. Energy trading on the blockchain demands domain expertise and introduces operational overhead. As Alam et al. (2017) point out, many energy providers have insufficient technical ability in deploying and maintaining the blockchain; therefore, they must rely on a third-party vendor. This will likely raise their costs. In addition, interoperability between blockchains and legacy systems is moving at an extremely slow pace. Devi et al. (2023) recommend the development of standards for the protocols for data exchange, but this solution faces delays in adoption. As contended by Mishra et al. (2023), interoperability solutions, including cross-chain technology, may have some promise but are still in the early days and, as such, their application for large-scale energy trading is at best limited. Some researchers advocate blockchain-as-a-service (BaaS) solutions, which will simplify deployment but at the risk of dependency on centralized providers and undermining some of the decentralized ethos driving blockchain development.

Table 4 provides a summary of the benefits and constraints of using blockchain technology in the trading of energy supply.

Table 4

Summary table of blockchains' integration on challenges in energy trading

Challenge	Positive Aspects	Limitations and Critical Perspectives	Citations
Scalability	Alternative consensus mechanisms (PoS, BFT) reduce resource usage.	Effectiveness varies; unproven scalability in real-world networks.	Ye et al. (2024); Devi et al. (2023); Mishra et al. (2023)
Data Privacy & Security	Advanced cryptographic solutions enhance privacy.	Computational complexity and limited adoption in public blockchains.	Piao et al. (2024); Zhang et al. (2020); Alam et al. (2017)
Regulatory Uncertainty	Hybrid models balance on/off-chain data for compliance.	Adds operational complexity; inconsistent cross-border regulatory frameworks.	Zhang et al. (2020); Devi et al. (2023); Mishra et al. (2023)
Environmental Impact	PoS and renewable-powered nodes reduce carbon footprint.	Limited regional adoption, high infrastructure costs for upgrades.	Gao et al. (2024); Tushar et al. (2020); Zhang et al. (2020)
Technical Complexity & Interoperability	Standard protocols and BaaS simplify integration.	Dependency on third parties and limited support for large-scale interoperability.	Alam et al. (2017); Devi et al. (2023); Mishra et al. (2023)

Note: Author constructed (2024)

RQ5: What emerging trends and potential future developments exist in blockchain-based P2P energy trading?

Integration of AI and Machine Learning (ML) with Blockchain. Among the most promising trends in blockchain-based P2P energy trading is the integration of AI and ML algorithms with a view to optimize energy markets. Proponents argue this will allow for more accurate predictions of energy consumption patterns, thus enabling prosumers to make more informed real-time decisions on when to buy or sell energy (Piao et al., 2024). Coupling AI with blockchain could, in theory, reduce energy wastage, improve grid stability, and enhance market efficiency. For example, AI can balance dynamically supply and demand to allow for more efficient trading.

However, critics raise the point that integrating AI and blockchain can be computationally highly resource-intensive, at least when scaled (Ye et al., 2024). Merging the power consumption of data processing in AI with the computational resource intensiveness in blockchain-particularly those dependent on PoW consensus algorithms-would therefore be very ecologically damaging. The newer consensus mechanisms, like PoS or PoA, may present an alternative to that, though their adoption remains patchy across different regions and industries (Devi et al., 2023).

Rise of Decentralized Autonomous Organizations (DAOs). Over the years, DAOs have found an increasing level of momentum for handling energy trading in these chains without having to necessarily rely on the services of any central intermediary. In DAOs, prosumers autonomously self-regulate by setting their own prices of energy or rules of trading via smart contracts that trigger themselves in automatic execution upon certain conditions based on predetermined parameters (Abdella et al., 2021). This provides for a more decentralized governance model that can result in democratic energy markets with more autonomous participants in charge of their energy activities.

As pointed out earlier, DAOs in energy trading are relevant when applied to regions with appropriate regulatory structures governing decentralized technologies. For example, in some parts of Europe and the United States, cleared regulatory sandboxes enable blockchain and DAOs and other decentralized governance structures' trial implementation. For instance, some countries like Germany and the Netherlands are keen to engage in pilot projects where

DAOs organize community microgrids, letting prosumers conduct self-managed energy trading (Guerrero et al., 2018). On the other hand, according to Chigwata and Ziswa (2018), the situation will be different for those areas where more stringent regulatory grip is given, such as parts of Asia and Africa, and where the law hardly recognizes decentralized forms of governance. They represent contexts in which traditional utility-driven frameworks are still dominant and underline how local regulatory conditions impact the feasibility of DAO adoption.

Despite the promise of DAOs, significant challenges remain for their widespread implementation. The legal status of DAOs varies greatly by jurisdiction, raising concerns about the enforceability of smart contracts that govern energy trades in some regions (Zhang et al., 2020). Secondly, a lot of criticism has widely been raised that a decentralized governance could lead to inefficiencies in decision-making processes because achieving consensus among an extensive number of participants slows down the process and enhances complexity (Messias et al., 2023). Ironically, this undercuts the efficiency gains that DAOs should theoretically provide, underlining once more the difficulty in balancing autonomy with operational efficiency in decentralized energy markets.

Focus on Sustainability and Renewable Energy. Another emergent trend in blockchain-based P2P energy trading is its increasing orientation toward sustainability. Blockchain enables the tokenization of Renewable Energy Credit (REC) and carbon credits, which could be traded at decentralized markets. Such an approach might incentivize the prosumers to adopt greener energy practices, since from now on, they can provide extra revenue from the selling of carbon offsets (Yao et al., 2024). Consequently, blockchain can help build more transparent and accountable carbon markets, encouraging transition to renewable energy.

However, some researchers argue that the environmental benefits of blockchain for energy trading are negated by the high energy consumption of many blockchain systems, particularly those relying on PoW (Gao et al., 2024). While PoS and other consensus algorithms are less power-consuming, these systems have not yet reached maturity, and their wide adoption is yet to gain momentum. Besides that, there also exist question marks over the scalability issues with regard to the newer models alone, particularly for the global energy markets (Mishra et al., 2023: Alghamdi et al., 2024).

Regulatory Evolution and Standardization. As blockchain technology matures, many governments and regulatory bodies are working to develop frameworks that accommodate blockchain in energy markets. In some jurisdictions, legislation is changing to acknowledge smart contracts as legally binding. For instance, the European Union is working on blockchain-specific regulations that would ultimately open the way for its use in energy systems (Zhang et al., 2020).

While such regulatory developments are promising, they are also fraught with challenges. Policy frameworks differ significantly across countries, creating inconsistencies that complicate cross-border energy trades. This mainly remains a barrier to wide adoption because many energy providers are still reluctant to invest in blockchain technology when there are no clear guidelines on how the use of blockchain technology will be regulated. Aside from this, regulatory processes that are often slow-moving simply cannot keep pace with rapid technological changes, leaving the energy companies to explore uncertain legal landscapes (Piao et al., 2024).

Energy Storage and Decentralized Grids. This will mark the new beginning in grid management all over the world, with decentralized energy storage and blockchain-based energy trading growing as a trend. With decreasing costs of energy storage technologies such as batteries, prosumers store excess energies when it is available and sell them during peak demand periods for making the grid flexible and stable (Alam et al., 2017). This trend is supported by blockchain technology, which enables tracking and verification of energy stored in real time, making DERs interact seamlessly with other broad energy grids.

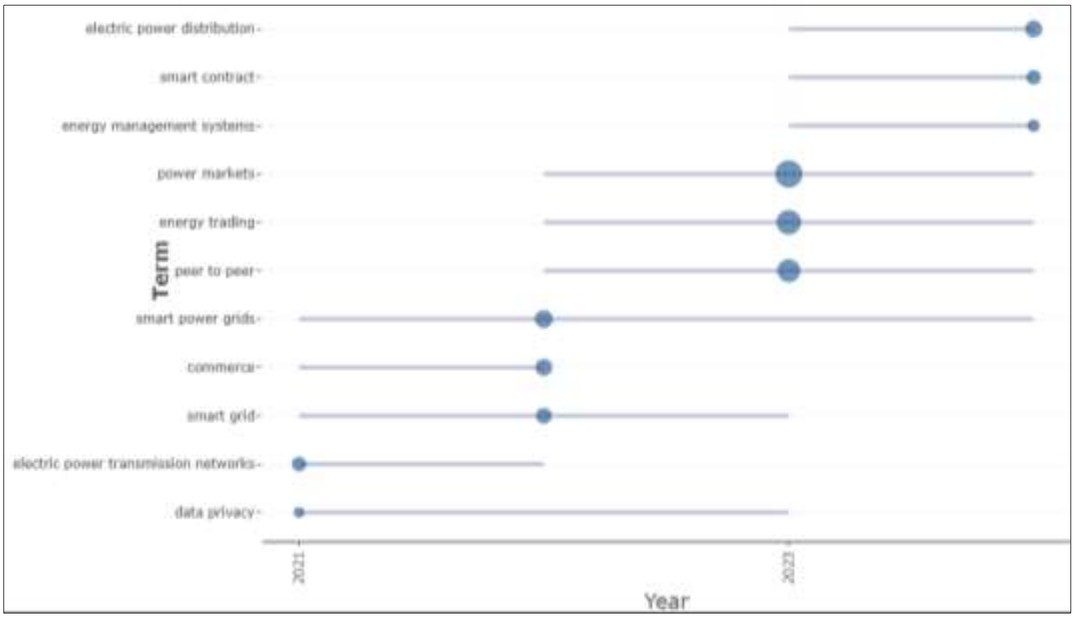
This trend is more pronounced in Europe, where countries like Germany and the Netherlands have supportive policies to propagate decentralized energy storage and blockchain-based energy exchanges. Several community-based energy trading pilot projects are underway in these countries, with prosumers participating in blockchain-enabled, secure, and transparent transactions of energy (Guerrero et al., 2018). Some US states, like California and New York, have initiated investigations into blockchain for energy storage, though those would have to align with a more controlled grid system and complexities under regulatory frameworks (Satchwell et al., 2019). In parts of Asia, countries such as South Korea and Japan showcase heightened interest in decentralized energy with increasing governmental support for renewable integration, though there are also technical and regulatory challenges (Alam et al., 2017).

Interoperability, especially with legacy grid technologies, remains one of the limiting factors toward scalability of blockchain systems in existing energy markets. Similarly, advancement on standardized protocols is fundamental for frictionless interaction between blockchain-based platforms and still developing legacy grids (Abdella et al., 2021). With the increased adoption of decentralized energy storage and hastening blockchain adoption, however, technical and regional challenges associated with these two continue to pose a determining role in realizing full-scale blockchain in energy markets.

The trend topics chart, given in figure 19, shows the evolution of key terms in blockchain-based P2P energy trading research over recent years.

Figure 19

Trend topics



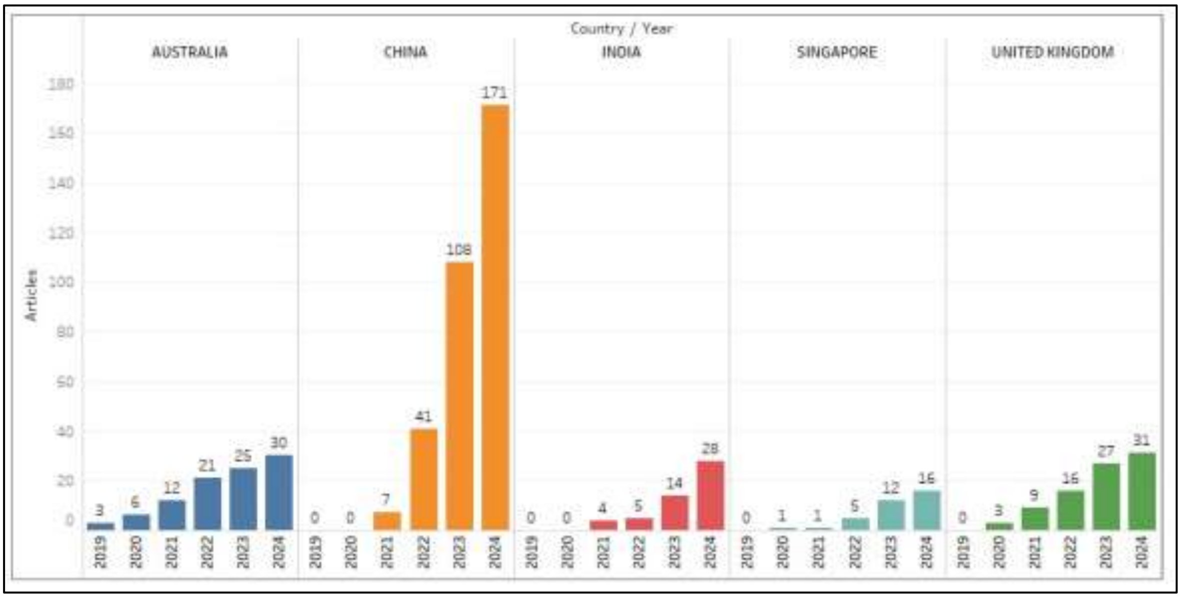
Note: Bibliometrix (2024)

Terms such as *"electric power distribution," "smart contract,"* and *"energy management systems"* have shown increasing prominence, especially from 2021 onward. *"Power markets"* and *"energy trading"* are also significant, reflecting the growing interest in decentralized trading systems and market structures. Emerging themes like *"data privacy"* and *"electric power transmission networks"* highlight concerns around security and infrastructure integration. This chart underscores the diversification of research, covering both technological advancements and regulatory issues.

The chart given in figure 20 provides an insightful look into the yearly production of articles focused on blockchain and energy trading from five countries: Australia, China, India, Singapore, and the UK.

Figure 20

Articles per year per over country



Note: Tableau (2024)

China stands out with a dramatic increase in publications, particularly in 2023 and 2024, with 108 and 171 articles, respectively, indicating a rapid acceleration in research activity. Australia and the UK show steady growth over the years, with 30 and 31 articles published in 2024, reflecting sustained interest in the field. India and Singapore, while contributing fewer articles overall, display significant jumps in 2024, with India publishing 28 and Singapore 16 articles. This data highlights China's leadership in this research area, followed by Australia's and the UK's consistent contributions.

4.4 Research Gaps and Future Direction

Despite numerous studies on blockchain’s technical capabilities, limited research has explored its social and economic impacts on the energy market. Future studies should address how blockchain technology influences energy accessibility, affordability, and user trust in decentralized systems. Additionally, studies focusing on the integration of blockchain with emerging technologies, such as AI and IoT, could provide insights into the potential for fully automated energy systems.

Chapter 05

Conclusions and Recommendations

5.1 Conclusions

The aim of this work is to discuss the transformative potential of blockchain in the area of P2P energy trading, especially in decentralized systems able to facilitate direct transactions among prosumers. The concept of blockchain has helped bring in a framework from where many of the pressing issues in the energy sector could be addressed: improvements in transparency and security, boosted operational efficiency while encouraging energy democratization in the process. Primary findings identified that although blockchain holds good promise in decentralized energy markets, there are considerable challenges that would have to be resolved before widespread adoption could be attained.

Conclusions from this research underline the advantages of blockchain, mainly related to the possibility of removing intermediaries and therefore transaction costs thanks to smart contracts. Smart contracts enable direct interaction by prosumers, creating an environment in which energy transactions can be performed efficiently and with total transparency. Scalability, however, remains a big issue, since all consensus mechanisms adopted today, like PoW, are particularly resource-consuming and not suitable for environments requiring high trading volumes. While PoS and BFT emerged as alternatives, these methods themselves are in the process of development and need further testing in real conditions with regard to their scalability and security.

Privacy and security were also identified as essential areas in need of more targeted solutions. Blockchain’s decentralized ledger provides transparency, yet it can inadvertently expose prosumers’ energy usage data, raising privacy concerns. Security challenges include vulnerabilities within smart contracts that can lead to data breaches or unauthorized access. Moreover, integrating blockchain with existing grid infrastructures presents technical interoperability issues that could hinder its scalability in conventional energy markets.

Lastly, the lack of a coherent regulatory framework was viewed to limit the possibility of blockchain in the energy market. Currently, the prevailing regulatory systems exist in light of the centralized system; there is ambiguity over the enforceability of smart contracts and data-sharing mechanisms across blockchains. In the absence of proper legal systems, innovation is inhibited and hence gives protectionist concerns for customers, hence challenging to deploy blockchain into the mainstream energy market. Thus, addressing these regulatory and interoperability challenges will be essential for blockchain's successful integration into energy markets.

5.2 Achievement of objectives

Objective 1 is met in Chapter 2 by discussing blockchain's potential to enhance transaction efficiency, transparency, and security through decentralized ledgers and smart contracts. Chapter 4 provides empirical findings that reinforce these benefits. Objective 2 is achieved by identifying key integration challenges, such as scalability, regulatory hurdles, and interoperability, with Chapter 4 providing data on these issues and Chapter 5 recommending solutions like hybrid consensus models. Objective 3 is covered by illustrating the advantages of blockchain in cost reduction, energy management, and consumer empowerment, with evidence from studies like the Brooklyn Microgrid presented in Chapter 4.

For Objective 4, the thesis compares the outcomes of blockchain implementation in terms of sustainability highlighting the positive and negative impact on the environment and Chapter 5 points to some environmentally friendly solutions such as PoS. Finally, the achievement of Objective 5 is accomplished through the specific suggestions given in chapter 5 where recommendations of how to address the existing challenges of blockchain in the implementation of P2P energy trading are provided.

5.3 Recommendations

To bridge the identified gaps and enhance blockchain's role in P2P energy trading, the following recommendations are proposed:

Adopt Hybrid Consensus Mechanisms. Understanding the shortcomings of PoW and PoS approaches for blockchain, such mechanisms of its further evolution could combine both scalability and power conservation. The integration of PoW's security to PoS or BFT designs can result in reliable structures for real-time trading. For instance, PoA can strengthen these approaches, as the addition of reputation to nodes enables to exclude cumbersome computations in the process of transaction confirmation while still improving the throughput of the system and maintaining its security.

Privacy-Enhancing Technologies (PETs). To address privacy concerns, technologies like zero-knowledge proofs (ZKPs) and multi-signature methods can protect participants' energy data while preserving verifiability. By encrypting and validating data, these tools allow users to control their information, a crucial step for blockchain's widespread adoption in P2P energy.

Regular Smart Contract Audits. Energy trading based on smart contract security requires regular audits that identify a priori vulnerabilities to be fixed before a smart contract is deployed. Collaboration with third-party auditors establishes standardized security measures that minimize these risks from potential attacks or errors, thus enhancing further the overall reliability of blockchain ecosystems.

Interoperability Protocols. Another important factor in scaling the energy solutions on the blockchain is the interoperability of the blockchain with the existing grid systems. This will mean standards development and an integration framework for coexistence with both decentralized and centralized systems. This, in turn, can be further helped through partnerships with traditional energy providers, smoothing transitions and enhancing compatibility.

Regulatory Sandboxes. Policymakers are encouraged to create regulatory sandboxes in which blockchain energy projects can be tested in a controlled environment. These will provide the opportunity for the regulator to keep the projects under close scrutiny, identify legal difficulties, and formulate a policy based on experience gained to strike a balance between innovation and consumer protection.

Renewable Energy Credits. Integrating RECs into blockchain systems might enhance both transparency and traceability of renewable energy use certification. Blockchain-based platforms can ensure a secure creation, trading, and verification process of RECs, blocking fraudulent claims and increasing confidence in renewable energy markets. This mechanism will go a long way to ensure users generate and trade in green energy while at the same time achieving sustainability objectives.

Dynamic Pricing and Automations. Integrating dynamic pricing mechanisms into energy trading on blockchain could further assist in the efficient distribution of energy, maintaining real-time balances between demand and supply. Furthermore, this could be combined with smart contracts to provide automated instantaneous pricing adjustments and seamless executions of trades, therefore facilitating efficient market operations and maximizing benefits for end-users (Kontos et al., 2024).

Integration with AI for Market Automation. Integration of blockchain with AI tools can further allow advanced market analysis and optimization. The algorithms powered by AI can predict energy demand and supply trends, pinpointing trading opportunities and recommending the most optimal trading strategies to the participants. This could lead to better efficiency and decision-making within the ecosystem of P2P energy trading, improving profitability and customer satisfaction.

5.4 Suggestions for Future Research

Firstly, scalability solutions remain critical; while existing consensus mechanisms like PoS and PoA offer efficiency benefits over PoW, their effectiveness across large-scale networks, especially in real-time energy trading, requires more empirical testing. Research into hybrid models that can combine benefits of multiple consensus mechanisms may offer insights into sustainable scalability.

Some of the emergent solutions for privacy and data protection techniques include zero-knowledge proofs and off-chain storage, but these introduce computational overhead. Thus, future research should be directed toward lightweight privacy-preserving approaches that preserve the velocity of transactions while keeping sensitive user data secure.

Besides that, interoperability issues between blockchains and existing infrastructures-such as smart grids and IoT-themselves present technical challenges. The research focus should be on standardized protocols necessary to bridge gaps between legacy systems and blockchains to allow smoother transitions to decentralized models.

In addition, regulatory frameworks for decentralized energy trading are at a nascent stage. Comparative studies of the regulatory frameworks across countries give valuable inputs about the policies that catalyse or inhibit blockchain adoption and hence help in formulating a balanced regulation framework that promotes innovation while safeguarding consumer interests.

Future research should address sector-specific analyses of the adoption of blockchain in peer-to-peer energy trading, such as residential, industrial, and commercial energy systems. By doing so, potential sector-specific challenges-such as scalability for industrial settings and affordability in residential markets-could be identified, along with tailored opportunities to improve the implementation of blockchain. This leads to better, more targeted, effective, and inclusive adoption strategies across a variety of energy sectors.

Finally, consumer behaviour and market acceptance make great intervention in the process of blockchain adoption in energy trading. Research into user attitude, motivation, and trust in decentralized systems will provide insight into the barriers to adoption that will enable the design of more user-cantered blockchain applications.

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