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Blockchain in the Energy Sector – Potential, Challenges, and Development Directions

Abstract: This paper examines the potential applications, challenges, and future directions for the development of blockchain technology in the energy sector in response to increasing demands for transparency, decentralisation, and system efficiency. The study explores how blockchain can support innovation across energy infrastructure and market operations, with particular emphasis on peer-to-peer energy trading, smart metering systems, and renewable energy certification. The research is based on a Critical Literature Review (CLR) that integrates recent interdisciplinary studies and case analyses. The findings indicate that blockchain offers significant opportunities to enhance transparency, automate transactions, and support decentralised energy governance. Evidence from international pilot projects and initiatives, including those implemented in Central and Eastern Europe, confirms both the feasibility of blockchain solutions and their added value in real-world energy environments. From a practical perspective, blockchain can enable targeted innovations in grid management, billing processes, and data integrity, although successful implementation will depend on clear regulatory frameworks, institutional readiness, and effective collaboration among key energy stakeholders. Furthermore, decentralised energy solutions supported by blockchain technology may strengthen consumer trust, promote local autonomy, and encourage broader public participation in energy transition processes. By focusing specifically on the needs and opportunities of the energy sector, this paper offers a fresh contribution to the discussion on digital public services and, by linking theoretical insights with practical applications, provides valuable guidance for researchers, policymakers, and public managers navigating the evolving landscape of digital energy governance.

Keywords: blockchain, energy sector, digital transformation, peer-to-peer trading, smart grids

Introduction

In recent years, the digital transformation of key infrastructure sectors such as energy has emerged as a strategic priority for governments worldwide. As energy systems face increasing demands for transparency, efficiency, and user-centric design, emerging technologies offer novel solutions to long-standing challenges. Among these, blockchain stands out as a revolutionary innovation with the potential to enhance trust, streamline data management, and redefine how energy networks are structured and operated. In an era where data integrity and transparency are no longer optional but essential, exploring blockchain's role in the public and energy sectors is both timely and necessary.

At its core, blockchain is a decentralised, distributed ledger that records transactions across a peer-to-peer network. It ensures data integrity through cryptographic security, consistent mechanisms, and stable records (Cole, Stevenson, Aitken, 2019; Wang, Han, Beynon-Davies, 2019). These characteristics make blockchain inherently resistant to manipulation, fostering transparency and trust in environments where multiple stakeholders interact without a centralised authority. The secure and traceable nature of blockchain systems makes them particularly relevant in multi-actor systems such as energy, where verifiability and auditability are critical.

The potential of blockchain to transform governance structures has not gone unnoticed by international institutions. Reports from the OECD, the World Bank, and the European Commission increasingly highlight blockchain's capacity to improve data sharing, enable secure digital identities, and foster cross-border compatibility of public services. As noted by the European Commission, 'distributed ledger technologies' could play a foundational role in delivering public value in areas such as voting, land registration, and public procurement. Importantly, these characteristics are being explored in the energy domain – including electricity trading, grid balancing, and renewable energy certification. Moreover, the

World Economic Forum (2015) predicts that by 2027, 10% of global GDP will be stored using blockchain technology – an indication of its growing importance in future economic and administrative systems.

Despite the increasing interest in blockchain technologies across various sectors, research on their application in energy systems – particularly at the regional and municipal level – remains fragmented and underdeveloped. While blockchain is frequently discussed in the context of business transformation and logistics (Kamran et al., 2021), its implications for energy governance and decentralisation are still not fully understood (Hooper, Holtbrügge, 2020). Most existing studies have focused on technical aspects, peer-to-peer networks, or private-sector use cases (Verma, Sheel, 2022), with a strong bias toward Bitcoin-related topics (Prasad et al., 2018; Li et al., 2018). This has led to a lack of comprehensive insights into blockchain's practical uses in areas such as smart contracts or licensing – both of which are highly relevant for distributed energy operations.

Moreover, in the domain of operations and supply chain management (OSCM), where parallels to energy logistics can be drawn, researchers have noted a persistent lack of exploration into how blockchain can impact or challenge the field (Cole, Stevenson and Aitken, 2019). Current OSCM studies have yet to fully address the opportunities and limitations that blockchain presents (Cole, Stevenson, Aitken, 2019), due to a shortage of real-world data and empirical validation (Sheel, Nath, 2019). Additionally, systematic reviews focusing on blockchain adoption in energy infrastructure and services are scarce (Verma, Sheel, 2022). In consequence, this paper addresses these gaps by focusing on the potential of blockchain in the energy sector, particularly in the context of Central and Eastern Europe (CEE), where the transition toward decentralised, renewable-based systems is intensifying. Drawing on regional examples, the study highlights how blockchain can enhance transparency, efficiency, and innovation in energy generation, distribution, and consumption.

The focus on Central and Eastern Europe is particularly relevant given the specific historical and institutional characteristics of energy systems in this region. Many CEE countries continue to operate highly centralised energy infrastructures shaped by post-socialist legacies, while simultaneously facing strong pressure to decarbonise, decentralise, and digitalise their energy sectors in line with European Union policies. These conditions create both constraints and opportunities for blockchain adoption, making the region a valuable empirical context for examining how decentralised digital technologies interact with established governance and market structures.

As Prasad et al. (2016) observed, over 80% of blockchain-related research has concentrated on cryptocurrencies like Bitcoin, with relatively few studies investigating other applications such as smart contracts, identity management, or licensing – tools highly relevant to emerging energy ecosystems.

Accordingly, the aim of this paper is to identify potential areas for blockchain applications in energy system transformation, with a particular focus on experiences from Central and Eastern Europe. Through critical literature review (CLR), this study investigates the following research questions:

1. What opportunities does blockchain technology offer for energy infrastructure and services?
2. How is blockchain being used in local and regional energy initiatives, particularly in the CEE region?
3. What are the possible future scenarios for implementing blockchain in the energy domain?

By addressing these questions, the paper advances understanding of how blockchain may support innovation in decentralised energy systems and proposes future directions for research and pilot implementations in the energy sector.

Method

The CLR approach facilitates a structured and in-depth synthesis of academic literature by critically analysing existing research, identifying knowledge gaps, and highlighting areas requiring further development. By employing this method, the study not only evaluates the resilience and limitations of previous findings but also highlights emerging patterns relevant to public-sector innovations.

To ensure the relevance and interdisciplinarity of the literature, sources were selected from domains such as energy systems, public administration, management, economics, and technology studies. The literature search was conducted using scholarly databases, including Google Scholar, Emerald Insight, and Cambridge Journals, selected for their comprehensive coverage of peer-reviewed publications and strong representation of works on governance and digital transformation.

A tailored keyword strategy was used to capture the multifaceted nature of blockchain applications in the public sector. Search terms included combinations of: “blockchain” AND “local government”, “energy sector”, “digital transformation”, “governance”, “potential”, “implementation”, “technology adoption”, “innovation”, and “organisational change”. Boolean operators were applied to refine search results and maintain thematic focus.

The following inclusion criteria guided the selection process:

– The article’s core subject had to be blockchain technology or its organisational implementation.
– Studies needed to discuss opportunities, limitations, or impacts of blockchain – particularly within the energy sector or governmental context.
– Articles were drawn from a variety of disciplinary perspectives to ensure a holistic view.
– Only research published within the last ten years (primarily from 2020 to 2025) was considered to reflect recent technological developments.
– Only English-language publications were included to ensure consistency in analysis and accessibility of sources.

The initial search provided 3,293 records, indicating broad scholarly interest in the subject. A rigorous, three-step selection process was then applied to filter the most relevant studies:

– Title and Abstract Screening: Articles were first screened based on their titles and abstracts. Publications focusing on blockchain possibilities unrelated to the public sector were excluded, narrowing the pool to 529 papers.
– Eligibility Assessment: The remaining articles were reviewed in detail to confirm alignment with the study’s focus, resulting in 140 eligible articles.
– Full-Text Review: A final selection was made through comprehensive content analysis. 42 publications were identified as directly addressing blockchain’s role, challenges, or potential within local government contexts and thus were included in the final review.

Importantly, the adopted CLR approach goes beyond a descriptive synthesis of existing studies. Rather than aiming for exhaustive coverage, the review focuses on identifying dominant research streams, contrasting perspectives, and conceptual tensions present in the literature on blockchain applications in the energy sector. Particular attention was paid to differences between technologically driven approaches and governanceoriented perspectives, as well as to inconsistencies between optimistic projections and regulatory or institutional feasibility. This critical lens also enabled the identification of underexplored areas, particularly regarding regional energy systems in Central and Eastern Europe, where empirical evidence remains limited.

This methodology, while broad, is not without its limitations. The selection may be subject to database bias, and the exclusion of non-English sources may have led to the omission of relevant international studies. Future research could mitigate these limitations by incorporating additional multilingual databases and expanding the search to include regional or grey literature, thereby enriching the global perspective on blockchain in public administration.

Literature review

As the discourse around digital transformation continues to evolve, blockchain technology has emerged as a subject of growing academic and institutional interest. A rich and diverse body of literature has developed in recent years, examining the theoretical foundations, structural characteristics, and real-world applications of blockchain across both private and public sectors. This literature review provides a structured overview of the current state of knowledge on blockchain, with a particular focus on how its principles and functionalities can demonstrate its potential for use in energy systems and infrastructure, particularly in Central and Eastern Europe (CEE). The following sections synthesise key scholarly contributions related to the definition, architecture, and practical relevance of blockchain, laying the groundwork for a deeper exploration of its applications, benefits, and challenges in energy contexts.

Blockchain foundations

Blockchain is widely recognised as a transformative digital innovation with growing relevance across multiple sectors. At its core, it is a distributed ledger technology that records transactions and other data in a secure and verifiable manner through cryptographic mechanisms and network consensus (Cole, Stevenson, Aitken, 2019; Wang, Han, Beynon-Davies, 2019; Zalan, 2018). Operating as a decentralised peer-to-peer system, blockchain enables participants to validate transactions without reliance on a central authority, thereby reducing vulnerabilities associated with single points of failure (Falwadiya, Dhingra, 2022; Topcu et al., 2024).

Once validated, transaction data are grouped into blocks and added sequentially to the ledger, making records effectively immutable and resistant to manipulation (Gurtu, Johny, 2019; Safa, Baeza, Weeks, 2019). This combination of decentralisation, cryptographic security, and immutability underpins blockchain's capacity to enhance transparency and trust in multi-actor environments where data integrity is critical. As a result, blockchain has attracted particular attention in sectors characterised by complex coordination processes and information asymmetries, including energy systems and markets.

Beyond secure recordkeeping, blockchain supports process automation through smart contracts – self-executing code that triggers predefined actions when specific conditions are met (Martinez et al., 2019). This functionality is especially relevant for energy-related applications such as peer-to-peer electricity trading, automated billing, and the certification of renewable energy, where timely execution, traceability, and trust among distributed participants are essential.

The characteristics of Blockchain

The relevance of blockchain technology for the energy sector is closely linked to a set of technical and organisational characteristics that distinguish it from traditional digital systems. Unlike centralised databases, blockchain operates on a decentralised architecture in which control over data and transactions is distributed across network participants rather than vested in a single authority (Wang, Han, Beynon-Davies, 2019). This feature aligns with ongoing transformations in energy systems, including the rise of distributed generation, prosumer participation, and local energy communities.

Beyond its foundational principles, blockchain is characterised by operational features that directly shape its applicability in data-intensive, decentralised sectors such as energy.

Additional features that distinguish blockchain systems include timestamped entries, distributed ledgers, user anonymity, and cohesive mechanisms (Singh et al., 2020; Falwadiya, Dhingra, 2022; OECD, 2018; Clohessy et al., 2019). Each transaction is linked to a previous one through cryptographic hashes and is further validated by structures such as Merkle

Trees, enabling tamper-proof data integrity (Alkhudary, Gardiner, 2024; Pal et al., 2021; Höhne, Tiberius, 2020; Tsiulin et al., 2020).

Transparency is another critical element. All participants have access to an up-to-date, shared version of the ledger, which significantly boosts transparency and accountability (Gurtu, Johny, 2019; Yeoh, 2017; Chatterjee et al., 2024; Verma, Sheel, 2022; Bonsón, Bednárová, 2019; Hald, Kinra, 2019). This openness, combined with blockchain’s resistance to single points of failure and its built-in traceability, enhances reliability and trust (Kant, 2021; Tiwari, Pal, 2023; Kouhizadeh et al., 2023).

Moreover, blockchain supports automation through smart contracts which enables real-time testing and validation of all transactions (Brender et al., 2024). These attributes are increasingly viewed as transformative for auditing, monitoring, and energy market reliability and renewable certification (Arianpoor, Borhani, 2024; Gurtu, Johny, 2019; Brender et al., 2024; Lin et al., 2023). However, while blockchain offers several strengths, it also presents limitations. Table I presents its key advantages and disadvantages.

Table I. Blockchain advantages and disadvantages

Advantages	Disadvantages
Decentralized control eliminates need for intermediaries	High energy consumption, especially in public blockchains
Enhanced data security through encryption and validation	Challenges due to network consensus mechanisms
Immutability ensures trustworthy records	Complexity and cost of implementation in existing administrative systems
Full transaction transparency	Legal and regulatory uncertainty in many jurisdictions
Improved accountability and traceability	Potential privacy issues due to transparent yet persistent nature of data
Real-time verification and automation via smart contracts	Limited understanding and technical expertise among public administrators
Resistance to tampering and fraud	Data storage limitations and increasing ledger size over time

Source: Own work based on: Wang, Han, Beynon-Davies, 2019; Franks, 2019; Gurtu, Johny, 2019; Clohessy, Acton, 2019; Höhne, Tiberius, 2020; Kouhizadeh et al., 2021; Brender et al., 2024; Martinez et al., 2019; Verma, Sheel, 2022; Singh et al., 2020; Topcu et al., 2024.

As illustrated in Table I, the strengths of blockchain lie in its core principles – decentralisation, security, transparency, and stability. These qualities are particularly appealing in the context of decentralised energy markets, where trust, verifiability, and reliable coordination among multiple actors are central concerns. At the same time, the limitations identified in the literature highlight the importance of regulatory clarity, technological scalability, and institutional readiness when assessing blockchain’s suitability for digital transformation in the energy domain.

Taken together, these characteristics explain why blockchain is increasingly explored as an enabling technology across multiple industries. In the energy sector – characterised by growing decentralisation, data intensity, and the need for transparent coordination among diverse stakeholders – blockchain-based solutions offer a particularly promising avenue for innovation. The following section therefore examines how blockchain is currently being applied across sectors, with a specific focus on energy-related use cases.

Current Applications of Blockchain – Sector Overview

Blockchain is increasingly recognised not only as a foundational technology behind cryptocurrencies, but also as a transformative force across numerous sectors of the economy and public life. As Höhne and Tiberius (2020) note, it is one of the most cutting-edge technologies available today, with the potential to be applied across diverse industries. Table II below summarises the key sectors currently exploring or implementing blockchain solutions, along with their primary use cases.

The variety of sectors currently experimenting with blockchain underscores its status as a foundational rather than just incremental technology. As Clohessy and Acton (2019) observe, blockchain could be as transformative as steam power or electricity, potentially laying the groundwork for new economic and social systems. Moreover, they describe blockchain as a “core technology” capable of redefining how societies and economies may function.

In the financial and accounting sector, blockchain is being used to increase the trustworthiness of financial data, improve risk management practices, and enable greater public oversight (Song et al., 2023). Research further suggests that blockchain has the potential to challenge traditional accounting practices and offer a completely new lens through which financial operations are known.

Supply chain and logistics are another area showing strong adoption. Tsiulin et al. (2020) highlight that while the potential remains largely un-

Table II. Overview of Blockchain Applications Across Sectors

Sector	Key Applications
Finance & Accounting	Transparent financial reporting, improved audit trails, public oversight, risk management
Supply Chain & Logistics	Traceability, fraud prevention, real-time tracking, smart contracts
Public Administration	Transparent governance, secure records, streamlined administrative processes
Corporate Governance	Stakeholder empowerment, enhanced transparency in decision-making
Industry 4.0 & Manufacturing	Decentralized production systems, real-time monitoring, data security
International Trade	Removal of intermediaries, faster cross-border transactions
Information Technology	Infrastructure for data sharing, integration with IoT and 6G
Strategic Management	Business model innovation, competitive repositioning

Source: Own work based on: Song et al., 2018; Tsiulin et al., 2020; Verma, Sheel, 2022; Singh et al., 2020; Arianpoor, Borhani, 2024; Mahmoud et al., 2025; Pal et al., 2021; Gurtu, Johny, 2019; Prasad et al., 2018.

tapped, blockchain could be revolutionary in increasing transparency and efficiency in global logistics systems. This aligns with broader expectations of blockchain’s economic impact, which was projected to reach over $176 billion by 2025 and exceed $3.1 trillion by 2030 (Falwadiya, Dhingra, 2022).

The private sector is also undergoing significant change. Blockchain enables new forms of stakeholder engagement and more transparent governance structures in corporations (Arianpoor, Borhani, 2024). It allows businesses to eliminate intermediaries and work with external partners as efficiently as with internal teams (Singh et al., 2020). As a result, companies are being pushed to reconsider strategic goals and develop new capabilities to stay competitive (Gurtu, Johny, 2019).

In the context of Industry 4.0, blockchain plays a central role. As Mahmoud et al. (2025) and Treiblmaier (2018) noted, this technology is increasingly seen as integral to the transformation of the global economy. When combined with other emerging technologies such as the Internet of Things (IoT) and 5G, blockchain opens new possibilities for innovation and collaboration.

Beyond these sector-specific applications, the broader societal and economic implications are profound. Blockchain offers a decentralised alternative to traditional authority structures, enabling systems where trust is established through technology rather than institutions (Kant, 2021; Hooper, Holtbrügge, 2020). It has the potential to reshape the very foundation of how business and governance are conducted. As Martinez et al. (2019) observe, blockchain is likely to evolve from a cost-saving tool to a platform enabling entirely new business models.

Finally, forecasts from major global institutions further validate blockchain’s potential. The World Economic Forum (2015) predicted that by 2027, 10% of global GDP will be stored on blockchain-based systems – a striking indication of how deeply embedded the technology could become in the fabric of the global economy.

While blockchain is still maturing, its current applications across finance, governance, logistics, and beyond point to a future in which decentralised, transparent, and secure systems could redefine public- and private-sector operations alike.

Applications of Blockchain in the Energy Sector

The integration of blockchain technology into the energy sector has gained significant traction in recent years, highlighting its transformative potential in how energy is produced, distributed, traded, and monitored. This momentum reflects a growing recognition of blockchain’s ability to enhance transparency, decentralisation, and efficiency across various dimensions of the energy value chain.

Companies such as Siemens have already begun applying blockchain in practice, particularly in power distribution and the optimisation of energy grid operations (Hooper and Holtbrügge, 2020). This real-world implementation demonstrates the technology’s ability to enhance traditional energy infrastructure. At the same time, there is an increasingly strong connection between blockchain innovations and broader developments in the energy industry, with many businesses actively exploring their use across sectors such as smart energy, healthcare, supply chains, and market oversight (Arianpoor, Borhani, 2024).

To provide a synthetic overview of the most frequently discussed blockchain applications in the energy sector, Table III summarises key use cases, their functional focus, and expected benefits as identified in the reviewed literature.

A particularly promising area of application lies in enabling decentralized energy systems. Blockchain supports peer-to-peer (P2P) electric-

Table III. Key blockchain applications in the energy sector

Energy system area	Blockchain application	Main function	Expected benefits	Key challenges
Peer-to-peer energy trading	Smart contracts for P2P transactions	Automated settlement of energy exchanges	Reduced transaction costs, prosumer empowerment, decentralization	Regulatory uncertainty, scalability
Renewable energy certification	Guarantees of Origin and energy tokenization	Verification and traceability of renewable energy	Increased transparency, trust, fraud reduction	Legal recognition, standardization
Smart grids and grid management	Distributed ledgers for grid data	Secure real-time data sharing	Improved grid reliability, data integrity	Interoperability with legacy systems
Microgrids and local energy communities	Blockchain-based governance platforms	Decentralized coordination and control	Community autonomy, local resilience	Institutional readiness, governance complexity
Billing and metering	Automated billing via smart contracts	Accurate and real-time settlement	Efficiency, reduced administrative costs	Data privacy, integration costs
Electric mobility	Blockchain-based EV charging platforms	Peer-to-peer access and payments	Flexible charging infrastructure, user trust	Network scalability, adoption barriers

Source: Own work based on: Höhne, Tiberius, 2020; Martinez et al., 2019; Wang, Han, Beynon-Davies, 2019; Gurtu, Johny, 2019; Clohessy, Acton, 2019; Arianpoor, Borhani, 2024; Brender et al., 2024; Verma, Sheel, 2022; Kant, 2021; Falwadiya, Dhingra, 2022.

ity trading, allowing individuals who generate their own power – such as through solar panels – to sell surplus energy directly to nearby users. This is exemplified by Power Ledger, a platform that facilitates real-time, transparent transactions between local energy producers and consumers (Martinez et al., 2019, p. 994). As Höhne and Tiberius (2020) observe, such innovations could reshape energy markets by making peer-to-peer exchanges more common, giving users greater autonomy in how and when they consume electricity, and even allowing them to select preferred energy sources.

Moreover, blockchain is recognised as a fundamental enabler of microgrids – decentralised, small-scale energy networks that support localised energy production and consumption (Höhne, Tiberius, 2020). Within these systems, blockchain facilitates peer-to-peer exchanges and community-level governance, pushing the sector toward more participatory and decentralised models (Höhne, Tiberius, 2020). These shifts align with broader goals of enhancing community control and sustainability in energy governance.

Beyond trading and traceability, blockchain can play a critical role in managing smart energy devices, supporting electric mobility infrastructure, certifying the origin of electricity, and improving billing and payment systems (Höhne, Tiberius, 2020). These functions not only streamline technical processes but also enhance user trust and system reliability.

Beyond user-facing applications, blockchain is increasingly discussed as a supporting infrastructure for system-level energy governance, particularly in the context of grid balancing and real-time coordination of distributed energy resources. As energy systems become more decentralised and variable – largely due to the growing share of renewables – grid operators face rising challenges related to flexibility, congestion management, and demand-supply synchronisation. Blockchain-based platforms may facilitate secure, transparent, and automated data exchange between transmission system operators, distribution system operators, aggregators, and prosumers, enabling more responsive and decentralised balancing mechanisms. In this sense, blockchain is not merely a transactional tool but a potential enabler of new coordination logics within complex energy systems.

Closely related to grid balancing is the emergence of local and regional flexibility markets, where distributed energy assets – such as storage units, electric vehicles, and demand-response resources – can provide system services. The literature increasingly points to blockchain as a technology capable of supporting these markets by enabling transparent verification of flexibility provision, automated settlement through smart contracts, and decentralised structures. However, studies also emphasise that such applications remain largely experimental and are strongly conditioned by regulatory design, interoperability with existing market platforms, and institutional acceptance. This highlights an important distinction between the theoretical potential of blockchain-based flexibility markets and their current level of practical maturity.

Taken together, these developments reveal blockchain as a versatile and powerful tool for the evolving energy landscape. Whether facilitating peer-to-peer transactions, verifying sustainable practices, or enabling smarter infrastructure, blockchain stands out as a key driver of innovation and decentralisation in the energy sector.

Discussion

The reviewed literature reveals several similar conclusions regarding the role of blockchain in the energy sector, alongside several important points of divergence. Most studies emphasise blockchain's potential to enhance transparency, automate transactions, and enable decentralised energy exchange. At the same time, the literature exposes tensions between technological optimism and the practical constraints associated with regulation, scalability, and institutional readiness. These contrasting perspectives suggest that while blockchain is widely perceived as a catalyst for energy system transformation, its real-world impact depends heavily on contextual factors such as governance structures, market design, and policy frameworks.

The findings from this review suggest that blockchain technology holds significant promise for transforming the energy sector, particularly in areas that demand transparency, trust, and efficiency. As evidenced by various international case studies and scholarly insights, blockchain has already begun to reshape how energy is produced, distributed, traded, and managed. From peer-to-peer energy trading platforms like Power Ledger to national grid innovations piloted by companies such as Siemens, real-world applications are no longer hypothetical but increasingly tangible (Martinez et al., 2019; Höhne, Tiberius, 2020).

A key insight from this study is the alignment between blockchain's technical characteristics – immutability, decentralisation, and transparency – and the operational needs of modern energy systems. Like public administration, where blockchain enables secure identity management or transparent records, the energy sector can leverage similar capabilities to ensure efficient energy trading, improved grid management, and better integration of renewable sources (Arianpoor, Borhani, 2024). In both contexts, blockchain reduces reliance on intermediaries and centralised control, offering faster, more democratic, and transparent flows of data and resources.

Numerous real-world initiatives demonstrate the growing adoption of blockchain in the energy sector, spanning diverse functions and geographic contexts. In Australia, the Power Ledger platform enables peer-to-peer (P2P) energy trading between households, allowing prosumers to sell excess solar energy directly to neighbours. A similar concept was piloted in the United States through the Brooklyn Microgrid project, where local energy exchange is facilitated via a decentralised platform. In Europe, the

Enerchain initiative brought together over 30 energy companies to test wholesale energy trading using blockchain, while the Netherlands’ Powerpeers platform gives consumers transparency and choice in selecting energy sources. In Estonia, Enefit has explored blockchain for renewable energy certification, aligning with the country’s broader digital strategy. The Share&Charge project in Germany applies blockchain to electric vehicle charging, enabling private individuals to share access to charging stations. Central and Eastern Europe has also seen early experimentation. In Poland, PGNiG piloted blockchain for secure storage of energy documentation, highlighting its potential for auditability and document integrity. Lithuania-based WePower introduced a system for tokenising future renewable energy production, offering a new financing model for green projects. Finally, global initiatives such as SolarCoin reward users for producing solar energy, using blockchain to trace and verify generation. These cases underscore blockchain’s versatility across energy value chains – from generation and distribution to billing, certification, and mobility – and suggest a strong foundation for future scaling, particularly in regions undergoing an energy transition, such as Central and Eastern Europe.

Despite this potential, however, several barriers remain. Technologically, the scalability and interoperability of blockchain systems pose persistent challenges, especially when integrated into legacy energy infrastructure (Acosta Llano et al., 2024; Wang, Han and Beynon-Davies, 2019). Legally, the lack of unified regulatory frameworks in the energy sector complicates large-scale deployment, particularly in multi-actor ecosystems such as microgrids. Socially, public awareness and institutional readiness remain limited, with many energy providers and consumers unfamiliar with blockchain-based platforms or hesitant to adopt new energy exchange models (Kant, 2021; Verma, Sheel, 2022). Despite this growing interest and expanding range of applications, the literature also highlights several persistent barriers to implementation.

Implementation barriers in blockchain-based energy systems

Despite the growing interest in blockchain-based energy solutions, the literature consistently identifies three categories of implementation barriers: regulatory, technological, and institutional. Regulatory barriers stem primarily from the absence of clear legal frameworks governing peer-to-peer energy trading, smart contracts, and data ownership in decentralised systems. Technological challenges include issues of scalability, interoperability with legacy energy infrastructure, and energy consumption associated with certain blockchain architectures. Institutional barriers, in turn, relate to limited organisational capacity, insufficient digital competencies, and resistance to change among energy providers and public authorities. The interaction of these barriers suggests that successful blockchain adoption in the energy sector requires coordinated action across technological development, regulatory design, and institutional learning.

Nevertheless, some countries and companies are actively moving forward. The EU's support for smart grid development and blockchain-driven certification systems, as well as pilot projects in Estonia and the Netherlands, highlight blockchain's role in enabling cleaner and more participatory energy systems (Höhne, Tiberius, 2020). For instance, the European Union has initiated the development of blockchain-based infrastructure to enable trustworthy, cross-border public services through a model rooted in transparency (Falwadiya, Dhingra, 2022; Curry, 2024). These examples reinforce the idea that blockchain is not merely a tool for optimisation but part of a broader digital transformation strategy in the energy sector.

What can energy stakeholders do now? While full-scale implementation may still be years away, energy regulators, grid operators, and local communities can begin with pilot projects in high-impact areas: peer-to-peer electricity trading, automated billing, renewable energy certification, or decentralised demand-response management. These initiatives can be based on permissioned blockchains that balance transparency with data privacy and control — making them particularly suitable for energy governance (Hald, Kinra, 2019; Haq et al., 2024; Mahula et al., 2024). Furthermore, collaboration between energy companies, technology providers, academic institutions, and prosumer groups can increase adoption, reduce implementation risk, and foster trust in new digital tools.

Importantly, blockchain should not be seen as a one-size-fits-all solution. Its effectiveness will depend on how well it is integrated into the complex technical, regulatory, and social fabric of the energy sector. As emerging best practices suggest, blockchain is most powerful when designed with interoperability, inclusiveness, and long-term scalability in mind.

Blockchain is not a silver bullet – but when thoughtfully applied, it can become a foundational element in the digital evolution of energy systems. Its capacity to enhance transparency, optimise processes, reduce costs, and support prosumer engagement positions it as a strategic enabler of next-generation, decentralised energy infrastructure.

Conclusions

This study explored the transformative potential of blockchain technology in the energy sector, with a particular emphasis on its applicability to decentralised, transparent, and efficient energy systems. The findings reveal that blockchain offers a robust framework for enhancing data integrity, operational transparency, system reliability, and user trust across the energy value chain. Practical use cases – such as peer-to-peer electricity trading, renewable energy certification, smart contracts, and grid optimisation – demonstrate how blockchain can reconfigure traditional energy structures toward more flexible, participatory, and digitally integrated models.

Despite its promise, blockchain adoption in the energy sector remains limited due to regulatory uncertainty, technical scalability challenges, and the complexity of integrating blockchain with existing infrastructure. Nevertheless, the experience of pilot initiatives across Europe and globally shows that decentralised technologies can function effectively even in highly regulated environments. These experiences underscore both the feasibility and benefits of using blockchain to support energy innovation, especially in regions such as Central and Eastern Europe, where energy transformation is a strategic imperative. This regional context illustrates both the structural constraints and the unique opportunities associated with implementing blockchain-based energy governance in regions undergoing rapid energy transition.

The research questions posed at the beginning of this paper have been addressed through a critical literature review. It has been shown that blockchain offers substantial opportunities to transform energy systems. Several pilot implementations – particularly in energy trading, certification, and microgrid management – illustrate its practical viability. However, broader adoption will require systemic coordination, cross-sector dialogue, supportive regulatory frameworks, and targeted capacity-building.

For practice, this means that energy regulators, utilities, and technology providers should begin by investing in blockchain literacy, identifying high-impact use cases (e.g., grid balancing or smart metering), and supporting collaborative pilot projects. Rather than aiming for immediate, large-scale deployments, stakeholders should adopt an incremental, modular approach that builds trust, technical knowledge, and stakeholder alignment over time.

Ultimately, blockchain is not a universal solution but a powerful enabler – one that, when integrated thoughtfully, can play a key role in the digital evolution of energy systems. The coming years will be crucial for evaluating its technical robustness, institutional fit, and long-term contributions to a more transparent, resilient, and decentralised energy future.

From a policy perspective, the findings suggest that blockchain should be approached not as a standalone technological solution, but as an enabling infrastructure embedded within broader energy governance reforms. Policymakers and public regulators play a crucial role in creating experimental regulatory environments, supporting pilot projects, and fostering collaboration between energy providers, technology developers, and local communities. Clear legal frameworks, combined with incremental implementation strategies, may significantly increase the likelihood that blockchain contributes to more transparent, resilient, and participatory energy systems.

Limitations and future research

The findings of this study highlight the untapped potential of blockchain technology to transform the energy sector, yet also point to the need for more nuanced and forward-looking research. While the transformative nature of blockchain is frequently emphasised, there remains a lack of structured frameworks to guide its implementation in energy infrastructure, particularly in decentralised systems and smart grid environments (van Hoek, 2019; Hooper, Holtbrügge, 2020). Furthermore, although broad reviews exist (Kant, 2021), the field lacks focused comparative studies that assess blockchain's benefits across specific energy applications – such as peer-to-peer energy trading, dynamic pricing, or renewable energy certification – similar to what has only recently begun in foreign trade and logistics contexts (Topcu et al., 2024).

With much of the blockchain research still leaning heavily on theoretical models and isolated pilot projects (Kamran et al., 2021; Sheel, Nath, 2019), future work should prioritise empirical investigations within national and regional energy systems. Given the observed predominance of Bitcoin-centred studies (Martinez et al., 2019), expanding research into energy market decentralisation, real-time metering, and prosumer engagement could open up new dimensions for energy transition. As Höhne and Tiberius (2020) rightly point out, the field needs visionary studies that not only assess current use cases but also anticipate the broader systemic and infrastructural impacts of blockchain. Such research could play a pivotal role in shaping the digital and sustainable future of the global energy sector – especially in regions like Central and Eastern Europe, where transformation is both necessary and urgent.

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Blockchain w sektorze energetycznym – potencjał, wyzwania i kierunki rozwoju

Streszczenie: Artykuł analizuje potencjalne zastosowania, wyzwania oraz przyszłe kierunki rozwoju technologii blockchain w sektorze energetycznym w kontekście rosnących oczekiwań dotyczących transparentności, decentralizacji oraz efektywności systemów energetycznych. W opracowaniu przedstawiono, w jaki sposób blockchain może wspierać innowacje w infrastrukturze energetycznej oraz funkcjonowaniu rynków energii, ze szczególnym uwzględnieniem handlu peer-to-peer, inteligentnych systemów pomiarowych oraz certyfikacji energii odnawialnej. Badanie opiera się na krytycznym przeglądzie literatury (Critical Literature Review – CLR), integrującym najnowsze interdyscyplinarne badania naukowe oraz studia przypadków. Wyniki analizy wskazują, że technologia blockchain oferuje istotne możliwości poprawy transparentności, automatyzacji procesów transakcyjnych oraz wspierania zdecentralizowanego zarządzania energią. Wnioski płynące z międzynarodowych projektów pilotażowych i inicjatyw, w tym realizowanych w Europie Środkowo-Wschodniej, potwierdzają wykonalność tej technologii oraz jej wartość dodaną w rzeczywistych warunkach sektora energetycznego. Z perspektywy praktycznej blockchain może wspierać ukierunkowane innowacje w obszarze zarządzania siecią, rozliczeń oraz integralności danych, przy czym skuteczne wdrożenie będzie uzależnione od jasnych ram regulacyjnych, gotowości instytucjonalnej oraz współpracy między kluczowymi podmiotami rynku energii. Jednocześnie zdecentralizowane rozwiązania energetyczne oparte na technologii blockchain mogą przyczyniać się do wzmacniania zaufania konsumentów, zwiększania lokalnej autonomii oraz aktywniejszego udziału społeczeństwa w procesie transformacji energetycznej. Artykuł wnosi nowe spojrzenie do dyskusji nad cyfrowymi usługami publicznymi, koncentrując się na specyficznych potrzebach i możliwościach sektora energetycznego. Dzięki połączeniu perspektywy teoretycznej z praktycznymi zastosowaniami stanowi wartościowe źródło wiedzy dla badaczy, decydentów publicznych oraz menedżerów odpowiedzialnych za rozwój cyfrowego zarządzania energią.

Słowa kluczowe: Blockchain, sektor energetyczny, transformacja cyfrowa, handel peer-to-peer, inteligentne sieci energetyczne (smart grids)

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