

**KAPITEL 5 / CHAPTER 5 <sup>5</sup>****INTEGRATING BLOCKCHAIN INTO ENERGY SYSTEMS: UNLOCKING  
TRANSPARENCY AND SUSTAINABILITY****DOI: 10.30890/2709-2313.2025-41-07-015****Introduction**

The global energy supply chain (ESC) - spanning extraction, processing, distribution, and consumption - faces growing pressure to enhance sustainability and transparency. Traditional centralized ESC systems raise concerns about accountability, efficiency, and environmental impact, often lacking transparency and traceability. These challenges hinder progress toward clean energy goals and undermine stakeholder trust. Blockchain technology, originally developed for cryptocurrencies, has emerged as a promising solution for addressing these issues. Its decentralized and transparent ledger system offers improved traceability, data integrity, and security. In energy contexts, blockchain can verify energy origin, enable secure decentralized transactions, and support the integration of renewable sources. This fosters greater trust in sustainability claims and enhances operational efficiency. Real-world pilot projects demonstrate blockchain's viability for energy transactions, grid management, and renewable energy certification. However, widespread adoption still faces obstacles such as regulatory uncertainty, interoperability, scalability, and integration with legacy systems. Addressing these challenges is essential to realizing blockchain's full potential in transforming energy supply chain management [1].

As global efforts to combat climate change intensify, the energy sector faces growing pressure to enhance sustainability and transparency. This shift demands a reassessment of current supply chain processes, particularly as renewable sources like wind, solar, and hydropower become more prominent. Blockchain technology aligns well with these goals, offering decentralized, secure, and transparent solutions that can transform energy production, distribution, and consumption [2].

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Global energy supply chains are complex and involve diverse regulations and stakeholders, making cross-border coordination challenging. Blockchain's decentralized architecture can help overcome these barriers by enhancing transparency, reducing fraud, and enabling secure international energy transactions. Notable examples include the Energy Web Foundation, which tracks renewable energy generation and usage, and Power Ledger, which facilitates peer-to-peer (P2P) energy trading, empowering consumers and decentralizing energy systems.

Beyond technology, sustainability in energy supply chains requires considering environmental, economic, and societal dimensions. Transparent systems allow for accurate environmental impact assessments, reduce long-term economic costs, and align with shifting consumer expectations for ethically sourced energy. As a result, transparency and sustainability are becoming strategic imperatives, not just regulatory requirements. This study explores blockchain's potential in advancing energy supply chain sustainability. It evaluates integration with emerging technologies, compares leading blockchain platforms (e.g., Ethereum, Solana, Hedera, Hyperledger Fabric), and examines real-world applications such as REC tokenization, dynamic pricing, and P2P trading. By doing so, it aims to inform stakeholders across academia, industry, and policy on blockchain's transformative role in building a cleaner, more efficient energy future.

## 5.1. Problem Review

Current energy supply chain management (ESCM) operates in a complex environment shaped by growing demands for efficiency, sustainability, and resilience. One major challenge lies in the fragmented structure of ESCs, involving multiple stakeholders with disconnected systems. This lack of interoperability hampers coordination, transparency, and data traceability across energy production, distribution, and sourcing. Consequently, verifying the environmental impact and sustainability of energy sources remains difficult-particularly as many ESCs still rely heavily on fossil fuels, contributing to climate change. Digitalization has introduced



new risks, especially cybersecurity threats targeting critical infrastructure. Regulatory complexity across regions further complicates ESCM, slowing innovation and technology adoption. Despite these challenges, there are significant opportunities. The falling cost of renewables, advances in clean technologies, and increased emphasis on sustainability support the transition toward greener energy systems. Emerging technologies such as blockchain and IoT can enhance security, transparency, and real-time monitoring within ESCs. Blockchain's decentralized ledgers can provide tamper-proof records, while IoT and smart grid systems improve efficiency, reduce energy losses, and enable better load management. Energy storage and demand response strategies also help balance supply and demand, enhancing grid resilience. Furthermore, international cooperation and the development of standardized processes can foster interoperability, facilitate energy trade, and strengthen stakeholder collaboration. In summary, while ESCM faces notable challenges, it also offers promising opportunities. Addressing inefficiencies and sustainability concerns will require joint efforts from policymakers, industry leaders, and technologists to adopt and scale innovative solutions. While blockchain is best known as the foundation for cryptocurrencies, its underlying principles-decentralization, transparency, immutability, and consensus-have far-reaching implications beyond digital currencies. Blockchain operates as a distributed ledger where transactions are securely recorded in sequential blocks, making data manipulation difficult and enhancing trust among stakeholders. These features make it a promising tool for transforming sectors like finance, coordination, and especially energy. In the context of energy supply chains (ESCs), blockchain offers solutions to longstanding challenges, such as lack of transparency, inefficiencies, and limited traceability. Literature highlights blockchain's potential to establish tamper-proof records of energy transactions, support decentralized trading through smart contracts, and improve system-wide security. Case studies illustrate practical implementations: the Energy Web Foundation's REC tokenization pilot in Georgia reduced transaction costs by 20% and improved speed and scalability; Power Ledger's P2P trading in Western Australia enabled households to exchange solar energy directly, improving grid stability and reducing costs [1].



Different blockchain platforms also offer unique capabilities. Solana enables up to 65,000 transactions per second (TPS) with minimal energy use due to its Proof-of-History consensus, while Hedera achieves over 10,000 TPS using the gossip protocol and sub-3 second confirmation times. Ethereum remains widely used for decentralized energy applications despite scalability limitations, which are being addressed through Layer-2 solutions like Optimism and Arbitrum. These have significantly increased Ethereum's throughput and reduced gas fees, making it more viable for large-scale energy use cases. Despite promising developments, blockchain implementation in ESCs still faces barriers such as regulatory complexity, limited interoperability, and scalability concerns. Existing literature reflects these challenges and emphasizes the need for empirical studies and performance benchmarks to evaluate blockchain's real-world viability in energy markets.

This study addresses those gaps by offering comparative assessments of major blockchain platforms-Ethereum, Solana, Hedera, Hyperledger Fabric, Polygon, and Polkadot-in the context of ESC applications. It integrates qualitative insights from peer-reviewed articles, technical reports, and case studies, while also aligning blockchain adoption with global policy frameworks such as the EU Green Deal and India's REC system. Future-focused technologies, including smart contracts, AI analytics, and REC tokenization, are also discussed to illustrate blockchain's evolving role in creating a more transparent, efficient, and sustainable energy ecosystem [2].

## 5.2. Transparency and Sustainability

Blockchain technology, with its decentralized and tamper-resistant ledger system, offers unprecedented transparency and security in energy transactions. Operating as a distributed database, blockchain ensures that all participants share access to the same transactional data. Each transaction is encrypted, added to a block, and cryptographically linked to previous blocks, forming an immutable chain. This structure enables every stakeholder-producers, consumers, and regulators-to verify the integrity of energy data independently, fostering trust and accountability across the



energy supply chain (ESC). Transparency is particularly critical in the energy sector, where historically opaque processes have hindered traceability and accountability. Blockchain's auditable architecture resolves these issues by making information on energy production, distribution, and source readily available. Smart contracts-self-executing agreements coded on blockchain-further enhance transparency and automation. For instance, upon verifying renewable energy generation via smart meters, a smart contract can automatically issue Renewable Energy Certificate (REC) tokens, track their lifecycle, and immutably record their transfer and retirement, thereby minimizing fraud and administrative overhead.

Moreover, smart contracts can dynamically adjust energy prices based on real-time supply-demand data gathered from IoT-enabled devices and smart meters. This dynamic pricing facilitates better grid management, improves the integration of intermittent renewable sources, and supports demand response strategies. As such, smart contracts play a vital role in promoting flexibility, efficiency, and responsiveness in ESC operations. Beyond energy, smart contracts have broader applicability in automating conditional transactions. By embedding contractual logic into code, they eliminate intermediaries, reduce delays, and mitigate human errors. For example, in supply chain contexts, smart contracts can trigger automatic payments once delivery is confirmed via sensor data. This level of automation ensures precision and enforceability without manual intervention. Importantly, smart contracts are transparent and publicly verifiable once deployed, enabling all involved parties to confirm terms and outcomes without requiring prior trust or shared legal frameworks. The immutability of blockchain ensures that once a contract is executed, it becomes a permanent and auditable part of the ledger. This feature minimizes disputes and provides a secure environment for transaction validation. Smart contracts also have the potential to streamline legal processes by replacing traditional contracts with code-based logic, reducing dependency on legal intermediaries. However, challenges remain. Smart contract code may not fully account for unforeseen circumstances or ambiguities, and the irreversible nature of blockchain can complicate dispute resolution or contract amendments. From a security perspective, blockchain leverages



cryptographic techniques to protect sensitive data and maintain integrity, making it well-suited for a digitized and interconnected energy sector vulnerable to cyber threats. Nonetheless, barriers to widespread adoption persist. These include regulatory hurdles, interoperability issues, and the technical complexity of integrating blockchain with existing energy infrastructure. Scalability also remains a challenge, especially when accommodating the high volume of global energy transactions. In conclusion, blockchain and smart contract technologies present a transformative opportunity for ESC management by enhancing transparency, automating complex processes, and improving data security. While technical and regulatory challenges must be addressed, their integration promises a more trustworthy, resilient, and efficient energy ecosystem. As adoption grows, blockchain is poised to play a critical role in reducing errors and fraud, ultimately contributing to the evolution of a more sustainable and secure energy future.

The integration of blockchain technology presents a significant opportunity to enhance the sustainability of the energy supply chain (ESC). With its decentralized, transparent, and immutable architecture, blockchain addresses persistent challenges in energy systems-particularly around transparency, accountability, and environmental compliance. By recording energy production, distribution, and consumption data in an incorruptible ledger, blockchain facilitates accurate monitoring of carbon emissions and verification of renewable energy generation, both of which are vital to sustainable energy governance [3].

Blockchain enables the creation of robust frameworks for Renewable Energy Certificates (RECs) and carbon tracking, allowing stakeholders to verify environmental claims with greater confidence. Smart contracts-self-executing protocols embedded on the blockchain can further automate and enforce sustainability measures. For instance, they may incentivize producers to meet specific environmental standards by triggering automatic rewards upon compliance.

One of the most transformative applications of blockchain in energy systems is peer-to-peer (P2P) trading. By leveraging smart contracts, prosumers (entities that both produce and consume energy) can trade surplus energy directly, bypassing traditional





intermediaries. Smart contracts govern transaction terms such as energy quantity, price, and verification through smart meters and ensure secure settlement and payment. These features reduce operational inefficiencies and promote decentralized energy exchange.

Traceability is particularly essential in renewable energy contexts, such as wind and solar, where claims of sustainability are susceptible to misreporting or manipulation. Blockchain's immutability ensures that these claims can be validated against an incorruptible historical record. Smart contracts play a vital role here by encoding regulatory compliance, emissions targets, and sustainability standards directly into the energy transaction process. For example, upon the generation of a certain amount of renewable energy, smart contracts can automatically issue tokenized RECs, serving as verifiable proof of compliance.

The integration of blockchain with real-time data inputs from IoT devices and sensors enhances the precision of traceability mechanisms. These devices continuously monitor energy production and distribution, feeding real-time data into the blockchain and ensuring that energy transaction records remain current and accurate. This dynamic traceability is especially valuable in cross-border energy trade, where multiple jurisdictions and regulatory frameworks are involved. By providing verifiable records of energy origin and compliance, blockchain can streamline international transactions, reduce administrative overhead, and foster trust among global stakeholders. Despite its promise, blockchain adoption in the energy sector faces several challenges. Effective implementation requires sector-wide collaboration, the development of standardized protocols, and regulatory alignment. Interoperability across platforms and integration with existing infrastructure also remain critical technical hurdles. In conclusion, blockchain technology offers a transformative pathway to enhance sustainability, transparency, and traceability in the energy sector. By leveraging decentralized ledgers and smart contract automation, the industry can build more accountable and reliable energy systems. As the technology matures and adoption expands, blockchain is poised to redefine global energy production, distribution, and trade promoting a more sustainable, efficient, and trustworthy energy ecosystem [3].

While blockchain technology offers transformative potential for the energy



supply chain (ESC), its effective implementation is challenged by a variety of technical, regulatory, economic, and organizational barriers. Understanding and addressing these limitations is crucial for integrating blockchain into the complex and highly regulated energy sector. **Scalability** is one of the primary technical limitations, particularly for public blockchain networks that process a large volume of transactions. The ESC inherently involves numerous, often real-time, transactions among diverse stakeholders. As transaction volumes grow, current blockchain infrastructures may struggle to maintain speed and efficiency. Although emerging solutions such as sharding and layer-two protocols (e.g., sidechains or state channels) are being developed to mitigate these issues, their adoption remains limited and underexplored in the energy sector context [2].

Another significant barrier is **interoperability**. The energy sector consists of a heterogeneous mix of stakeholders' utilities, grid operators, prosumers, regulators each employing distinct legacy systems and digital infrastructures. Integrating blockchain technology across such a fragmented ecosystem requires the development of standardized communication protocols and data models. Without cross-platform interoperability, blockchain solutions risk becoming siloed and ineffective. Consequently, international standardization efforts and collaborative initiatives are essential to ensure seamless integration and communication across systems [3].

The **regulatory landscape** also poses challenges. The decentralized and transparent characteristics of blockchain can conflict with existing regulatory frameworks, which often assume centralized control and linear accountability. As the energy industry is subject to strict regulatory oversight, integrating blockchain demands proactive engagement with regulatory bodies. This includes modifying existing policies or creating new regulatory frameworks that accommodate blockchain-based processes while ensuring legal compliance [4].

In parallel, **data privacy** remains a critical concern. Energy transactions frequently involve sensitive information, such as consumer behavior patterns, financial data, and contractual terms. Although blockchain ensures transparency and data integrity, balancing these with confidentiality is a complex task. To address this issue,





researchers are exploring privacy-preserving technologies such as zero-knowledge proofs and homomorphic encryption, which can offer enhanced data protection without compromising transparency [5].

The **environmental impact** of blockchain is another consideration, especially in a sector dedicated to sustainability. Proof-of-work (PoW) consensus mechanisms used by some blockchain platforms are highly energy-intensive. This contradicts the energy sector's goals to reduce carbon footprints. Transitioning to more energy-efficient consensus mechanisms such as proof-of-stake (PoS), delegated proof-of-stake (DPoS), or proof-of-authority (PoA) is essential for aligning blockchain adoption with sustainability objectives.

In addition to technical and regulatory constraints, **awareness, and education** present non-trivial barriers. Blockchain remains a nascent technology, and many stakeholders including energy providers, policymakers, and the public lack a clear understanding of its benefits and limitations. Educational initiatives are therefore critical to promoting informed decision-making and fostering widespread acceptance.

**Financial costs** represent another significant barrier. Implementing blockchain in the ESC involves substantial upfront investments, including the development of smart contracts, the integration of blockchain with existing systems, and the establishment of secure blockchain networks. For smaller or less-resourced organizations, these costs can be prohibitive. Strategic partnerships, public funding mechanisms, and cost-sharing models may be necessary to facilitate adoption across all stakeholder groups.

Despite their advantages, **smart contracts** are not without risks. Coding errors, logic flaws, or inadequate testing can lead to unintended outcomes or security vulnerabilities. In critical sectors like energy, such issues can have far-reaching implications. As such, rigorous auditing, testing, and verification processes are necessary to ensure the reliability and resilience of smart contracts in ESC applications [6].

From a policy perspective, emerging frameworks such as the **European Union (EU) Green Deal** and **India's Renewable Energy Certificate (REC) system** provide valuable guidance for blockchain adoption in energy systems. The EU Green Deal



outlines a digital transformation pathway toward climate neutrality by 2050, including the tokenization of RECs and the establishment of decentralized energy trading platforms [7]. Similarly, India's REC system incentivizes renewable energy generation by enabling renewable producers to earn and sell RECs to conventional producers for compliance with Renewable Purchase Obligations (RPOs). Blockchain can enhance these frameworks by automating REC issuance, improving the traceability of energy transactions, and reducing fraud through immutable recordkeeping. Nonetheless, to ensure that energy systems remain legally compliant and technically viable, **regulatory challenges** surrounding blockchain must be proactively addressed. Regulatory frameworks should include provisions for data privacy, cross-border energy exchange, and carbon emissions tracking. Future policies must prioritize **interoperability standards**, enabling seamless interaction between blockchain systems operating in different authorities. This will be critical for developing interconnected, cross-border energy markets and realizing blockchain's full potential in global energy governance.

## Conclusion

This study has provided a comprehensive analysis of the transformative potential of blockchain technology within the energy supply chain (ESC), highlighting its ability to enhance transparency, security, efficiency, and sustainability across various segments of the energy sector. By enabling immutable and transparent ledgers, blockchain ensures the traceability and auditability of energy transactions, while smart contracts and decentralized consensus mechanisms eliminate the need for centralized intermediaries, reducing transaction time and operational inefficiencies. The analysis revealed that different blockchain platforms offer unique advantages depending on specific ESC applications. Public platforms like Ethereum and Polygon are well-suited for decentralized energy trading and micro-transactions, whereas permissioned platforms such as Hyperledger Fabric are ideal for enterprise-scale applications involving compliance and regulatory oversight. High-throughput platforms like Solana and Hedera Hashgraph support real-time energy data management essential for IoT-



integrated smart grids. Moreover, the interoperability offered by platforms like Polkadot provides the technical foundation for integrating localized energy systems into national and international grids.

The study also identified key emerging trends such as the convergence of blockchain with IoT, edge computing, and AI that enable real-time automation, dynamic pricing, and predictive maintenance. Tokenization of renewable energy assets and the use of zero-knowledge proofs (ZKPs) further expand the scope of blockchain by providing financial innovation and privacy-preserving data sharing. These advancements pave the way for more democratic and resilient energy markets.

Several actionable recommendations have emerged:

- Platform selection should align with specific ESC use cases.
- Regulatory frameworks need to adapt to accommodate decentralized technologies.
- Investment in quantum-resistant cryptography is essential to safeguard blockchain systems.
- Public–private partnerships should be encouraged to scale infrastructure and blockchain adoption.
- Educational and usability-focused initiatives are critical for user engagement.
- Decentralized Autonomous Organizations (DAOs) should be explored for managing community-driven energy initiatives.

Collectively, these insights confirm that blockchain has the potential to serve as a foundational technology for modernizing the ESC, supporting the transition toward decentralized, transparent, and renewable energy systems.