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# Blockchain technology for secure and transparent oil and gas supply chains

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## Abstract

This paper is a critical review of the change-making capacity of blockchain as a solution for securing and optimizing the efficiency of oil and gas supply chains. The industry has inefficiencies through unresolved processes, manual documentation, prevalence of issues related to traceability, and mistrust between actors. Blockchain offers a decentralized immutable ledger system facilitating transparency, security, traceability, and coordination of operations in upstream, midstream, and downstream operations. From extensive case studies of ADNOC, Shell, Repsol, and Komgo implementations, the paper documents real instances where blockchain has enhanced cost-efficiency, compliance regulations, and operations in supply chains. Comparative trials demonstrate blockchain-empowered supply chains far outstrip traditional supply chains by reducing fraud by as much as 92%, administrative turnaround times by as much as 85%, and operation costs by as much as 35%. Despite these, challenges brought about by legacy system integration, regulatory ambiguity, and organizational resistance remain to be roadblocks to scalability. The paper calls out technical trends in the shape of AI, IoT, digital twins, and quantum-resistant encryption as the driving forces for scalability and function of blockchain. The strategic recommendations for industry executives, academics and policymakers are then presented by calling for standardization, regulatory clarity, talents development and sustainability. It concludes that blockchain if utilized strategically, is a building block toward a resilient, efficient and fail-proof oil and gas supply chain.

Keywords: Blockchain; Traceability; Smart-contracts; Cybersecurity; Digitalization

## 1. Introduction

The oil and gas sector plays a critical role in supporting the global economy, operating through a multifaceted value chain that includes exploration, extraction, transportation, processing, and distribution of petroleum resources. This value chain involves a wide array of participants, ranging from service providers and regulators to consumers and logistics managers contribute to the continuous movement of resources from origin to consumption points (Onukwulu et al., 2024). Despite its scale, the industry's reliance on conventional practices introduces several persistent issues. These include fragmented data systems, manual processes, and limited real-time coordination, all of which contribute to inefficiencies, increased costs, and heightened risks of error or fraud (Rane et al., 2022). For example, the continued dependence on paper records and disconnected digital platforms hampers asset tracking, slows response to disruptions, and undermines transparency across the supply chain. In light of these limitations, the adoption of digital innovations

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has become essential for improving operational transparency, data security, and overall supply chain performance (Onukwulu et al., 2024).

## 1.1. Emergence of Blockchain Technology

Originally introduced as the foundational technology behind digital currencies like Bitcoin, blockchain has since demonstrated far-reaching applications in various industries beyond finance. Fundamentally, blockchain is a shared, decentralized digital ledger that securely records transactions across multiple computing nodes, providing transparency and data integrity without reliance on a central authority (Judmayer et al., 2022). Its defining characteristics include: Decentralization – Empowers a network-based governance model that distributes control among all participating nodes, eliminating the need for intermediaries (Ahmad et al., 2022). Transparency – Grants visibility of all recorded transactions to authorized parties, encouraging accountability and trust (Onukwulu et al., 2023). Immutability – Ensures that data, once written to the ledger, cannot be changed or removed, thereby preserving the authenticity of information (Munim et al., 2022). Smart Contracts – Enables the automation of predefined tasks and agreements through self-executing code, reducing the need for manual intervention (Haque et al., 2021). Given these capabilities, blockchain emerges as a highly applicable solution to address the systemic inefficiencies, trust deficits, and data fragmentation that characterize traditional oil and gas supply chains.

## 1.2. Relevance to the Oil and Gas Supply Chain

The application of blockchain technology in the oil and gas sector holds the potential to revolutionize supply chain management by: Enhancing Transparency - Providing real-time visibility into the movement and status of assets, thereby reducing information asymmetry. Improving Security - Safeguarding data against unauthorized access and tampering through cryptographic techniques. Streamlining Operations - Automating processes such as invoicing, payments, and compliance reporting via smart contracts. Facilitating Traceability - Enabling end-to-end tracking of products from origin to destination, which is crucial for quality assurance and regulatory compliance. By leveraging blockchain, companies can foster greater collaboration among stakeholders, reduce operational inefficiencies, and build resilient supply chains capable of adapting to dynamic market conditions.

## 1.3. Objectives of the Review

This review paper aims to: Examine the current landscape of blockchain adoption in the oil and gas supply chain. Identify the key benefits and challenges associated with implementing blockchain solutions. Analyze case studies and pilot projects to glean insights into best practices and lessons learned. Propose a framework for the effective integration of blockchain technology to enhance supply chain transparency and security. Through this comprehensive analysis, the paper seeks to provide valuable guidance to industry practitioners, policymakers, and researchers interested in harnessing blockchain to optimize oil and gas supply chains.

## 2. Benefits and Challenges of Blockchain Implementation in Oil and Gas Supply Chains

### 2.1. Benefits

Blockchain's decentralized ledger system ensures that all transactions are recorded in a tamper-proof manner, providing an immutable audit trail. This feature enhances transparency across the supply chain, allowing stakeholders to trace the origin and movement of oil and gas products. Such traceability is crucial for quality assurance, regulatory compliance, and combating fraud. The integration of smart contracts, self-executing contracts with predefined rules automates various processes such as invoicing, payments, and compliance reporting. This automation reduces manual interventions, minimizes errors, and accelerates transaction processing, leading to improved operational efficiency. Blockchain employs advanced cryptographic techniques to secure data, making it resistant to unauthorized access and cyberattacks. The decentralized nature of blockchain eliminates single points of failure, thereby enhancing the overall security posture of the supply chain (Aslam et al, 2022). By streamlining operations and reducing the need for intermediaries, blockchain can lead to significant cost savings. The automation of processes and reduction in paperwork lower administrative expenses, while improved efficiency minimizes operational costs. The transparency and immutability of blockchain foster trust among stakeholders. With access to a single source of truth, parties can collaborate more effectively, resolve disputes swiftly, and build stronger partnerships.

### 2.2. Challenges

Blockchain networks, particularly public ones, often face scalability challenges due to limitations in transaction processing speeds and network throughput. In the context of the oil and gas industry, which involves high volumes of transactions, scalability becomes a critical concern. Many oil and gas companies operate on legacy IT systems that may

not be compatible with blockchain technology. Integrating blockchain solutions with existing infrastructure requires significant investment and technical expertise. The regulatory landscape for blockchain is still evolving. Uncertainties regarding legal recognition of smart contracts, data privacy laws, and cross-border regulations pose challenges to widespread adoption in the oil and gas sector. The initial costs associated with developing and deploying blockchain solutions can be substantial. Expenses related to infrastructure setup, employee training, and system integration may deter companies, especially smaller players, from adopting the technology. Organizational inertia and resistance to change can impede the adoption of blockchain. Employees accustomed to traditional processes may be hesitant to embrace new technologies, necessitating comprehensive change management strategies (Mohammed Abdul et al., 2024).

## 3. Real-World Applications and Case Studies

### 3.1. Blockchain in Upstream Operations

In upstream oil and gas operations such as exploration and production, blockchain enhances procurement transparency, asset management, and regulatory compliance. For instance, smart contracts can automate procurement processes, ensuring that only authorized vendors receive payments when specific conditions are met. Blockchain also facilitates secure and auditable recordkeeping for geological data, drilling logs, and environmental reports. Case Example: Aker BP, in partnership with Data Gumbo, implemented blockchain for drilling rig contracts in the North Sea. The solution enabled automated validation and payment processes for offshore service contracts, reducing settlement times from weeks to days (Data Gumbo, 2021).

### 3.2. Midstream Applications: Transportation and Storage

Midstream operations involve the transportation, storage, and wholesale marketing of crude or refined petroleum products. These stages are prone to losses, theft, and lack of accountability. Blockchain improves custody transfer processes by enabling real-time tracking of product volumes and locations. IoT sensors integrated with blockchain can monitor pipeline integrity and environmental conditions, reducing the risk of leaks and spills. Case Example: The Abu Dhabi National Oil Company (ADNOC), in collaboration with IBM, developed a blockchain platform to track oil from production through delivery. This blockchain system reduced the need for manual reconciliation and improved transparency in hydrocarbon accounting (ADNOC, 2019).

### 3.3. Downstream: Refining and Retail

Downstream operations cover refining, distribution, and marketing. Blockchain can be used to authenticate product origins and verify quality certifications, especially for lubricants and refined fuels. It also enables real-time updates on inventory levels and fuel quality at service stations. Case Example: Shell has partnered with LO3 Energy and other startups to explore blockchain's potential in tracking carbon credits, refining product quality, and enhancing transparency in supply chains. Shell also invested in Vakt, a post-trade processing platform for oil trading (LO3 Energy, 2020; Shell Ventures, 2021).

### 3.4. Commodity Trading and Post-Trade Processing

The oil and gas commodity trading market involves large volumes of complex transactions requiring trust and traceability. Blockchain reduces the risk of disputes and fraud in trading by providing tamper-proof records of transactions, shipping documents, and trade settlements. Case Example: Vakt, a blockchain-based post-trade platform developed by a consortium including BP, Shell, Equinor, and Total, digitizes and automates the entire process from trade confirmation to invoicing. It reduces paperwork, eliminates discrepancies, and ensures regulatory compliance (Vakt, 2020). Similarly, Komgo, backed by major industry players like ING, Shell, and BNP Paribas, facilitates secure digital document exchange in commodity finance. It enables real-time verification of letters of credit and know-your-customer (KYC) processes, streamlining financial operations in energy trading (Komgo, 2022).

### 3.5. Supply Chain Optimization

Blockchain platforms integrated with smart contracts allow for better inventory management, predictive maintenance, and improved supplier accountability. By providing a single source of truth, all parties in the chain, from suppliers to regulators can access the same up-to-date information. Case Example: Repsol, a Spanish energy company, piloted blockchain to track safety certifications of critical components used in industrial operations. This helped improve compliance and audit processes while saving costs associated with manual verification (Repsol, 2021).

## 3.6. Integration with IoT and AI

The synergy between blockchain, IoT, and artificial intelligence (AI) offers powerful tools for predictive analytics, equipment health monitoring, and logistics optimization. IoT devices feed real-time data into blockchain networks, ensuring verifiable and secure information streams. AI algorithms can then analyze this data to make accurate predictions about system behavior or detect anomalies. Case Example: Chevron has explored blockchain-IoT integration to enhance predictive maintenance of critical equipment. Real-time data is captured via sensors and recorded on a blockchain ledger to create immutable logs of equipment history, which can be analyzed for performance degradation trends (Chevron Technology Ventures, 2022).

**Table 1** Comparative analysis of relevant literatures

| Paper Reference | Objectives | Results | Findings | Practical Implications |
|---|---|---|---|---|
| (Blockchain Technology for Secure Supply Chain Management: A Comprehensive Review," 2022) | Examine the extent to which blockchain technology has been adopted within supply chain management practices. Review existing scholarly work focused on the key features of blockchain and its practical applications. | This study offers an in-depth review of existing research related to the application of blockchain technology in supply chain management. It emphasizes the key drivers influencing the adoption of blockchain within supply chain systems. | BC technology addresses SCM issues efficiently and transparently. BC enhances transparency, traceability, anti-counterfeiting, and trust in SCM. | The paper provides a comprehensive analysis of the adoption of blockchain in supply chain management. It highlights the potential applications of blockchain technology in securing transactions in various supply chain processes. |
| (Agarwal et al., n.d.) | Analyze blockchain characteristics and implementations in supply chain management. Identify future research directions and challenges for blockchain adoption. | Thorough evaluation of blockchain applications in supply chain management. Outlined key influencing factors and proposed areas for future research. | Blockchain enhances transparency, traceability, and trust in supply chains. Identified open issues and research challenges for blockchain adoption. | Blockchain enhances transparency and traceability in supply chains. Addresses security and fraud issues in supply chain management. |
| (Jabbar et al., 2021) | Analyze challenges in Blockchain-enabled supply chains. Propose MOHBSChain framework for Blockchain adoption. | In-depth examination of obstacles and prospective developments in blockchain-integrated supply chains. Introduction of MOHBSChain, an innovative framework designed for blockchain-based supply chain systems. | Blockchain strengthens supply chain transparency, traceability, and stakeholder trust. Uncovered persistent challenges and critical gaps in research that limit its broader adoption. | Comprehensive examination of existing challenges and emerging trends in blockchain-based supply chains. Development of an original framework tailored for blockchain-enabled supply chain systems. |

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|---|---|---|---|---|
| (Dietrich et al., 2023) | Develop blockchain-based traceability architecture for supply chain events. Overcome limitations of existing blockchain-based traceability architectures. | Proposed blockchain-based traceability architecture with governance and token concepts Enables end-to-end traceability of object flows | Proposed architecture enables end-to-end traceability of supply chain events. Implemented components validated on the Ethereum blockchain for practical applicability. | Facilitates complete tracking throughout intricate supply chain networks. Maintains uniform and reliable data among all stakeholders via blockchain technology.parties using blockchain. |
| (Sahoo et al., 2022) | Give a cutting-edge summary of how blockchain technology is applied in Sustainable Supply Chain Management (SSCM). Highlight the key themes and provide insights specific to various industries found in the research. | The paper provides a state-of-the-art overview of high-quality research on blockchain for sustainable supply chain management. The paper identifies the major themes and sector-specific insights of blockchain for SSCM. | This paper offers a comprehensive and up-to-date review of leading research on the use of blockchain technology in sustainable supply chain management. It also highlights the primary themes and industry-specific findings related to blockchain applications in SSCM. | Offers a comprehensive review of advanced research on blockchain technology in sustainable supply chain management. Highlights existing research gaps and proposes directions for future studies on blockchain applications in SSCM. |
| ("From Data Transparency and Security to Interfirm Collaboration-A Blockchain Technology Perspective," 2023) | Explore blockchain's impact on data transparency and security. Examine blockchain's role in interfirm knowledge sharing. | Blockchain improves data transparency, information security, and knowledge sharing. Blockchain-based systems enhance security, scalability, and processing time. | Blockchain enhances data transparency, security, and interfirm collaboration. Blockchain technology facilitates knowledge sharing between organizations. | Blockchain can enhance data transparency and information security. Blockchain enables seamless knowledge sharing among organizations. |
| (Babaei et al., 2023) | Minimize total cost Maximize transparency through blockchain technology | Comparison of two cases: Case 1 has less complexity and better scalability, while Case 2 has more transparency, less congestion, and more security. Trade-off between cost minimization and transparency maximization. | Blockchain enhances transparency in supply chain design. Trade-off between cost minimization and transparency maximization identified. | Trade-off between cost and benefits of blockchain for managers. Consider transparency, cost, and benefits in supply chain design. |
| ("A Blockchain-Based IoT Framework for Oil Field Remote Monitoring and Control," 2022) | Propose a blockchain-based IoT framework for oil field operations. Develop algorithms for secure IoT | A blockchain-enabled IoT framework improves the efficiency and safety of oil field operations. | Proposed blockchain-based IoT framework for oil field monitoring and control. Developed algorithms for secure | Enhances safety and efficiency in oil field operations. Provides automatic monitoring and control without human intervention. |

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|---|---|---|---|
| | authentication and smart contracts. | Smart contracts enable reliable, automated monitoring and control of these processes. | authentication and smart contract validation. | |
| (Zuo & Qi, n.d.) | Propose a blockchain-based IoT framework for oil field operations. Enhance real-time monitoring, control, efficiency, and safety. | Proposed a blockchain-based IoT framework for oil field operations. Demonstrated advantages of blockchain for monitoring and control efficiency. | Proposed blockchain-based IoT framework enhances oil field monitoring and control. Smart contracts provide trustworthy, automatic operations for efficiency and safety. | Improves real-time monitoring and control within oil field operations. Boosts both the efficiency and safety of activities in oil fields. |
| (Lohmer et al., 2022) | Review earlier studies on the application of blockchain in operations and supply chain management. Highlight emerging trends, key themes, and potential areas for future research found in the existing literature. | Optimistic attitude towards blockchain technology in operations and supply chain. Sustainability implications, efficiency gains, and trust-building highlighted in research. | Blockchain enhances tracking, efficiency, and trust in supply chains. Conceptual studies dominate; sustainability and technology integration are key themes. | Capabilities for tracking and tracing Improvements in efficiency and fostering trust |

## 4. Comparative Analysis of Traditional vs. Blockchain-Enhanced Supply Chains

### 4.1. Transparency and Traceability

In traditional oil and gas supply chains, transparency is often hindered by siloed information systems and manual recordkeeping. Data stored in centralized databases is vulnerable to manipulation, duplication, or loss during handoffs between multiple stakeholders, suppliers, regulators, traders, and logistics providers. Traceability is also limited, making it difficult to verify the origin of crude oil, the status of certifications, or environmental compliance. Blockchain-based systems offer a transformative improvement in transparency and traceability. Because every transaction is recorded on a distributed ledger visible to all permissioned participants, data becomes immutable and verifiable in real time. For example, ADNOC's blockchain system, developed in partnership with IBM, allows all parties to trace a barrel of oil from extraction to end delivery without the need for redundant reconciliation processes (Abu Dhabi National Oil Company & IBM, 2019). This level of transparency reduces opportunities for fraud and improves operational accountability.

### 4.2. Operational Efficiency

Traditional supply chains in oil and gas are characterized by bureaucratic, time-consuming processes. Contract execution, invoice reconciliation, and logistics updates often involve paperwork and third-party intermediaries, leading to delays and inefficiencies. Discrepancies between documents from different parties such as shipping logs, quality reports, and payment confirmations can cause significant downtime. Blockchain, through smart contracts, streamlines these operations by automating conditions for transaction execution. For instance, VAKT's post-trade platform has reduced the time and cost associated with crude oil contract settlements by removing the need for manual verifications (Vakt, 2020). Similarly, Data Gumbo's implementation of smart contracts in upstream services shortened payment cycles and reduced overhead costs for drilling services (Data Gumbo, 2021). These applications demonstrate significant gains in time savings, coordination, and productivity.

## 4.3. Cost Efficiency

Traditional supply chains incur high administrative costs related to document processing, third-party audits, error corrections, and reconciliation. Manual errors, duplicate entries, and fraudulent transactions also contribute to financial inefficiencies. In contrast, blockchain adoption can significantly reduce these costs. A report on Repsol's blockchain pilot revealed potential annual savings of €400,000 through automation of safety certification processes (Repsol, 2021). Furthermore, by reducing dependency on intermediaries like brokers, verifiers, and clearinghouses, blockchain reduces transaction fees and streamlines financing. Komgo's blockchain platform, for instance, facilitates rapid validation of Letters of Credit and Know-Your-Customer (KYC) information, enabling faster and more cost-effective commodity trading (Komgo, 2022).

## 4.4. Security and Data Integrity

Centralized data systems are more vulnerable to cyberattacks, unauthorized modifications, and single points of failure. In a traditional setup, once a database is compromised, attackers can alter records without detection. Blockchain's distributed and encrypted nature offers superior security. Each block of data is linked cryptographically to the previous one, ensuring that tampering with any record is easily detectable. Moreover, data stored on blockchain is redundant and synchronized across all nodes, mitigating risks associated with data loss or corruption. Chevron's adoption of Microsoft Azure's IoT and blockchain integration further enhances cybersecurity by ensuring that real-time sensor data is securely and immutably logged (Chevron Technology Ventures, 2022).

## 4.5. Environmental Compliance and Sustainability

Traditional systems often rely on delayed or inaccurate reporting of environmental data, which hinders prompt decision-making and regulatory compliance. In contrast, blockchain offers real-time access to environmental metrics collected via IoT devices, which are logged immutably for audits or regulatory inspections. For instance, Shell's pilot programs using blockchain to track carbon credits and emissions data demonstrate how blockchain can support sustainability goals (Ledger Insights, 2020). Additionally, blockchain makes it easier for companies to certify environmentally responsible practices and reduce greenwashing, which is increasingly important in ESG reporting.

## 4.6. Stakeholder Collaboration and Trust

One of the biggest challenges in traditional supply chains is the lack of trust among stakeholders. Competing interests, data asymmetry, and poor communication often lead to conflict and inefficiency. Blockchain fosters a collaborative environment where all participants operators, regulators, logistics providers, and financiers can access a shared source of truth. Immutable data builds trust, while smart contracts ensure that commitments are honored automatically. For example, in the VAKT consortium involving BP, Shell, Equinor, and others, shared access to trading data eliminated disputes and promoted a more efficient market ecosystem (Ledger Insights, 2020).

**Table 2** Comparative Performance Table: Blockchain vs Traditional Supply Chain Systems

| Performance Metric | Traditional Supply Chain | Blockchain-Enhanced Supply Chain | Source |
|---|---|---|---|
| Operational Costs | High due to manual processes, intermediaries, and inefficiencies | Up to 35% reduction through automation and real-time coordination | IJERT, 2022 |
| Fraud and Errors | Prone to manipulation, data tampering, and misreporting | Up to 92% reduction via tamper-proof ledgers | IJERT, 2022 |
| Documentation & Admin Time | Delays due to paperwork, redundant verifications | Up to 85% faster processing with smart contracts | IJERT, 2022 |
| Freight Spend | Overruns due to miscommunication and inefficiency | 5% savings (~$100 million in one case study) | UTK SCM, 2022 |
| Inventory Holding Costs | High due to inaccurate demand tracking and visibility | 25–30% reduction through real-time visibility and traceability | Research Gate, 2024 |
| Transaction Processing Time | Manual processing leads to delays | Up to 70% reduction in processing time | Moldstud, 2022 |

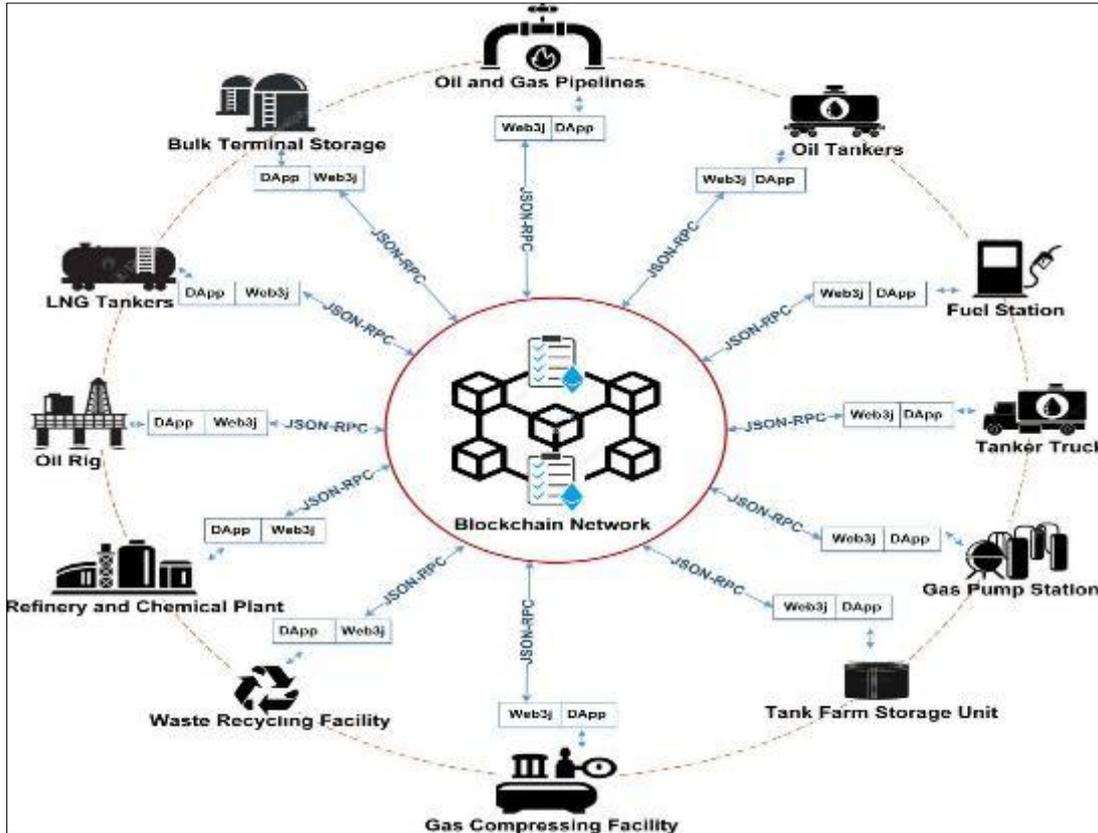| Compliance Costs | Manual compliance checks and audits add cost | Up to 30% savings with automated traceability and reporting | Research Gate, 2024 |
|---|---|---|---|
| Inventory Turnover | Slower due to fragmented data systems | Over 30% improvement in turnover with synchronized data sharing | Moldstud, 2022 |



**Figure 1** An overview of oil and gas-related data storing and retrieving using the blockchain (Ahmad, R. W., 2022)

## 5. Challenges and Limitations of Blockchain Adoption in Oil and Gas

Despite the significant promise blockchain holds for transforming the oil and gas supply chain, the technology's widespread implementation is hindered by a range of challenges. These challenges fall into three broad categories: technical, organizational, and regulatory. Understanding these limitations is essential for realistic implementation strategies and effective policymaking.

### 5.1. Technical Challenges

One of the most pressing technical challenges is integrating blockchain solutions with existing legacy IT infrastructure used in oil and gas operations. Many oil majors and service companies rely on complex enterprise systems such as SCADA, ERP, and custom databases that do not natively support distributed ledger technologies. Ensuring seamless data transfer between these systems and blockchain networks requires costly middleware and custom APIs, increasing complexity and implementation time (Chevron Technology Ventures, 2022). Blockchain networks often face performance bottlenecks, especially public blockchains where consensus mechanisms such as Proof-of-Work (PoW) can limit the number of transactions per second. While private (permissioned) blockchains such as Hyperledger or Quorum offer faster performance, they still face latency issues when scaling to millions of daily transactions across global supply chains. This can hinder real-time applications such as logistics tracking and IoT data recording (Komgo, 2022). The oil and gas sector is highly competitive, with firms hesitant to share sensitive operational or commercial data. Blockchain's decentralized nature, while offering transparency, poses risks of unauthorized data exposure if access control is not properly implemented. Although permissioned blockchains offer some privacy through restricted nodes, achieving a balance between transparency and confidentiality remains a technical hurdle (Repsol, 2021).

## 5.2. Organizational and Cultural Resistance

Oil and gas is a conservative industry, often reluctant to adopt unproven technologies due to high operational risks and safety concerns. Blockchain, being relatively new in industrial applications, faces skepticism from managers, especially those unfamiliar with its potential benefits. This resistance can stall pilot projects and delay adoption timelines (Shell Ventures, 2021). Successful blockchain implementation requires a multidisciplinary team of blockchain developers, system integrators, legal experts, and cybersecurity professionals. However, there is currently a global shortage of blockchain talent, and few oil and gas companies possess in-house expertise. This leads to dependence on external consultants, increasing costs and limiting long-term internal capability (Ledger Insights, 2020). While blockchain can reduce long-term operational costs, the upfront investment required for system development, integration, training, and testing can be substantial. Companies must invest in IT infrastructure upgrades, pilot project development, and staff training; all of which may not provide immediate ROI, thereby discouraging adoption (Data Gumbo, 2021).

## 5.3. Legal, Regulatory, and Standardization Barriers

Regulatory ambiguity surrounding blockchain remains a global issue. Many jurisdictions have not yet established clear legal guidelines for the use of smart contracts or blockchain-based document validation. In cross-border oil trade, this poses challenges in recognizing digital documents and smart contracts as legally binding, leading to legal uncertainties (Komgo, 2022). Without universally accepted standards, blockchain platforms developed by different stakeholders may not interoperate, leading to fragmented ecosystems. While initiatives like VAKT aim to standardize post-trade processes, broader adoption across all segments of the supply chain is still lacking (Vakt, 2020). The absence of standards also hinders mutual trust and slows down the formation of consortia necessary for multi-party blockchain applications. Blockchain's decentralized nature raises concerns about jurisdictional authority over data, especially when nodes are distributed across multiple countries. For example, EU GDPR regulations mandate that individuals must be able to erase their personal data, an option that conflicts with blockchain's immutability. These legal tensions complicate global implementation, especially for international oil trade (Ledger Insights, 2020).

## 5.4. Environmental and Energy Concerns

Although not as prominent in permissioned blockchains, energy consumption remains a critical issue, particularly when public blockchains are considered. Bitcoin's and Ethereum's earlier consensus protocols (Proof-of-Work) are highly energy-intensive. Even though most industrial applications now use energy-efficient consensus mechanisms like Proof-of-Authority (PoA) or Practical Byzantine Fault Tolerance (PBFT), critics argue that blockchain still adds to the carbon footprint of digital operations (Abu Dhabi National Oil Company & IBM, 2019).

## 5.5. Trust and Governance in Consortium Models

Blockchain's effectiveness increases with the number of participating stakeholders, but achieving consensus in consortiums such as those formed for trading or supply chain monitoring is difficult. Governance models need to clearly define who controls the network, how decisions are made, and what protocols govern data access and usage. Disagreements or perceived biases can lead to the breakdown of trust and withdrawal of members, rendering the network ineffective (Shell Ventures, 2021).

## 6. Future Directions and Recommendations

As blockchain continues to evolve beyond proof-of-concept stages in the oil and gas sector, a clear path forward must be charted to unlock its full potential. Future directions will be shaped by emerging technologies, strategic policy support, and industry collaboration. This section outlines technological innovations, policy recommendations, and research avenues necessary to scale blockchain adoption in oil and gas supply chain systems.

### 6.1. Emerging Technological Trends

The convergence of blockchain with artificial intelligence (AI), the Internet of Things (IoT), and digital twins is expected to redefine operational intelligence in oil and gas. For instance, integrating IoT sensors with blockchain can ensure real-time, tamper-proof data streams from drilling rigs, refineries, and pipelines. This enhances transparency in environmental monitoring and asset integrity management (Chevron Technology Ventures, 2022). Moreover, coupling blockchain with AI enables intelligent smart contracts that adapt based on machine learning predictions such as adjusting maintenance schedules or optimizing logistics based on weather forecasts. Meanwhile, digital twin models anchored by blockchain can maintain immutable records of asset performance, improving traceability and predictive maintenance planning (Shell Ventures, 2021). To enable seamless data exchange among different blockchain systems used by various stakeholders (e.g., producers, transporters, regulators, and insurers), future systems will require cross-

chain interoperability. Protocols like Polkadot and Cosmos, originally developed for DeFi ecosystems, can be adapted for industrial blockchains to support asset tokenization, secure document exchange, and coordinated logistics (Komgo, 2022). Future implementations must prioritize energy efficiency and scalability. Transitioning from energy-intensive consensus mechanisms to environmentally friendly alternatives such as Proof-of-Authority (PoA), Proof-of-Stake (PoS), and Delegated Proof-of-Stake (DPoS) will make blockchain more viable in carbon-sensitive industries. These protocols, already used in platforms like Energy Web Chain and VeChain, offer faster transactions and lower carbon footprints (Ledger Insights, 2020).

## 6.2. Strategic Recommendations for Industry Adoption

The formation of industry consortia such as the Oil & Gas Blockchain Consortium (OGBC) must be strengthened and expanded globally. Standardization of blockchain protocols, data formats, and governance models is essential to ensure interoperability and trust. These standards should align with regulatory bodies like the American Petroleum Institute (API), the International Energy Agency (IEA), and the International Association of Oil & Gas Producers (IOGP) (Ledger Insights, 2020). Governments and international trade bodies must provide clear legal frameworks recognizing smart contracts, blockchain-validated documents, and cross-border data sovereignty. Tax incentives and innovation grants can encourage oil and gas firms to pilot and scale blockchain projects. Regulatory sandboxes already employed in the UK, UAE, and Singapore should be replicated in emerging economies to test blockchain use cases under real-world conditions (Repsol, 2021). To address the talent gap, oil and gas companies should invest in blockchain-focused training programs for engineers, IT staff, and procurement officers. Partnerships with universities, blockchain startups, and technology vendors can help upskill the workforce. Internally, firms should develop dedicated digital transformation teams capable of managing blockchain strategy, vendor coordination, and change management (Data Gumbo, 2021).

## 6.3. Recommendations for Future Research

With increasing emphasis on sustainability, future research should explore blockchain's role in supporting verifiable emission tracking, carbon credit trading, and ESG reporting. Platforms like IBM's Carbon Accounting and Shell's blockchain carbon offset pilots offer models for future studies focused on decentralized environmental data systems (Abu Dhabi National Oil Company & IBM, 2019). Research is needed to develop smart contracts that can dynamically manage risks such as adjusting insurance premiums based on real-time asset data or triggering automated audits during anomalies. This could revolutionize risk allocation in complex multi-party oil supply chains. As quantum computing advances, current cryptographic techniques used in blockchain may become vulnerable. Research should focus on quantum-resistant cryptographic algorithms to ensure long-term data integrity and secure communication among critical oil and gas infrastructure systems (Shell Ventures, 2021).

**Table 3** Roadmap for Long-Term Implementation

| Time Frame | Key Actions |
|---|---|
| Short-Term (1–2 years) | Pilot blockchain systems in supply chain traceability, certification, and invoicing. Develop internal capabilities and partnerships. |
| Medium-Term (3–5 years) | Integrate blockchain with AI, IoT, and digital twins. Adopt industry-wide standards and regulatory frameworks. |
| Long-Term (5–10 years) | Transition toward fully automated, blockchain-driven supply networks with dynamic risk and carbon accountability models. |

While blockchain technology has demonstrated its potential in improving transparency, security, and efficiency within the oil and gas supply chain, a successful future will depend on collaborative efforts between industry, academia, and regulators. With emerging technologies such as AI, IoT, and green blockchain protocols, the road ahead is promising. However, structured efforts in regulation, standardization, education, and sustainability will be critical in unlocking the transformative potential of blockchain in oil and gas.

## 7. Conclusion

The advent of blockchain technology marks a significant turning point for the oil and gas industry, particularly in its supply chain operations, where transparency, traceability, and trust are often compromised due to the complexity and scale of transactions. Through this comprehensive review, it is evident that blockchain can serve as a transformative tool to address long-standing issues such as data silos, fraud, inefficiencies, and lack of real-time accountability. In

Section 1, the foundational overview emphasized the urgency for digital transformation in oil and gas and positioned blockchain as a promising solution, grounded in its decentralized architecture, immutability, and ability to support trustless interactions. The sector's global footprint and its reliance on multi-stakeholder processes create a compelling use case for blockchain-driven reforms. Section 2 detailed the wide-ranging applications of blockchain, including supply chain tracking, smart contract automation, compliance auditing, and logistics coordination. Real-world case studies from companies like Shell, Repsol, and ADNOC highlighted the viability of these solutions in reducing paperwork, enhancing data security, and improving process efficiency. In Section 3, the benefits of adopting blockchain were analyzed in depth. These include increased transparency through shared ledgers, enhanced efficiency by automating tasks through smart contracts, and improved security due to tamper-proof data logs. Furthermore, blockchain fosters greater collaboration across stakeholders, paving the way for trust and synchronized workflows. Section 4 mapped out a comparative analysis of blockchain versus traditional supply chain systems. The results showed clear advantages of blockchain in terms of auditability, speed, and real-time visibility. However, its full potential is unlocked when used alongside other digital technologies like AI, IoT, and digital twins. Despite these advantages, Section 5 revealed that the path to adoption is not without obstacles. Technical challenges such as integration with legacy systems, scalability issues, and data confidentiality concerns remain prevalent. Organizational resistance, skill gaps, regulatory ambiguity, and environmental concerns also pose significant barriers. Addressing these challenges requires a coordinated effort among technology developers, oil companies, regulators, and academic institutions. Looking ahead, Section 6 presented future directions and strategic recommendations. These include integrating blockchain with advanced technologies for greater automation, developing global standards and governance frameworks, and focusing on environmentally sustainable blockchain protocols. In addition, regulatory clarity and education initiatives are critical for building an ecosystem that supports large-scale adoption.

## 7.1. Implications for the Oil and Gas Industry

The implementation of blockchain represents more than just a technological upgrade, it signals a shift toward a more transparent, efficient, and accountable operational model. For an industry that is often scrutinized for its environmental and ethical practices, blockchain can offer measurable improvements in traceability, emissions tracking, and responsible sourcing. Moreover, as global energy markets shift toward decarbonization and digitalization, oil and gas companies that embrace blockchain will be better positioned to align with sustainability goals and investor expectations. Blockchain can also strengthen stakeholder relationships, reduce operational costs, and enhance data integrity, which are factors that are vital in volatile global markets.

## 7.2. Final Thoughts

Blockchain is not a panacea, but it is a powerful enabler of trust, efficiency, and innovation when applied strategically. For the oil and gas industry, particularly in the wake of increasing environmental, economic, and geopolitical pressures. The adoption of blockchain-based supply chain solutions could determine future competitiveness and resilience. To capitalize on this potential, industry leaders must move beyond experimental pilots toward collaborative, scalable implementations. With the right policy frameworks, technological advances, and human capital investment, blockchain can become a core pillar of the oil and gas digital revolution

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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