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Revolutionizing the energy sector: exploring diversified blockchain platforms for a sustainable future

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Blockchain technology has caused a significant transformation in the global energy sector as it is increasingly applied in producing, distributing, trading, and managing energy. The incorporation of blockchain in the industry presents unprecedented opportunities for creating secure and decentralized systems of trading energy systems that are not only secure and resilient but also transparent. The paper explores a detailed analysis of various blockchain platforms and endeavors to collapse the existing gaps in the advanced research of blockchain systems supporting the development of energy trading applications. Precisely, this paper gives in-depth details of some of the popular blockchain platforms, and it primarily focuses on the platforms' security, scalability solutions, consensus methods, strategies for mitigating cyberattacks, privacy-preserving mechanisms, regulatory considerations, the integration of artificial intelligence for platform optimization and suitability in energy trading based on the existing information. It helps energy providers select the best blockchain platform for their energy trading projects. The detailed examination aims to further improve energy trading efficiency, reliability, and sustainability via the most suitable blockchain platform.

KEYWORDS

blockchain, energy sector, blockchain platforms, scalability, cyberattacks, privacy-preserving mechanisms, regulations, artificial intelligence

1 Introduction

Blockchain technology was established with the emergence of Bitcoin in 2009 (Devika and Ramesh, 2023). Blockchain technology records electronic data in a decentralized manner on a ledger and is distributed across several nodes (computers) or networks. It also secures data that cannot be altered with it uses principles such as transparency, immutability, and consensus in recording or validating transactions and information (Nitin et al., 2020).

The security feature is one of the main benefits of Blockchain technology (Remya and Aneena, 2018). Due to the incorporation of cryptographic methods and decentralization, the technology is very hard to tamper and hack, thus promoting data reliability and confidentiality (Sathya and Barnali, 2020). Moreover, blockchain platforms are recognized for its energy-saving capability. Conventional Centralized systems utilize much more energy to process and verify data than blockchain networks (Asma et al., 2019).

Extremely low power consumption is caused by a variety of consensus technologies that remove the necessity for energy-intensive mining procedures such as Proof of Stake (PoS) and Proof of Authority (PoA) (Bahareh and Petr, 2021). This approach reduces energy consumption since in PoS and PoA, validators will hold more cryptocurrencies. Scalability is a factor that has to be considered in blockchain. Blockchain should be scalable to handle a large volume of transactions without affecting the network speed. Even when the energy demand increases (Dodo et al., 2021; Symiakakis and Kanellos, 2024).

Proof of Work (PoW), another consensus method is utilised by blockchain networks like Bitcoin (Christophe, 2021). In PoW, miners have to solve complex math puzzles to create new blocks and confirm transactions. Although PoW is effective in ensuring network security, one of the drawbacks is its high energy consumption. Overall, blockchain technology makes energy transactions safe, transparent, and efficient, which is helpful for managing and trading energy in today's energy sector.

1.1 Limitations of traditional energy systems

Traditional energy markets have always been controlled by intermediaries, centralised organizations, and regulatory frameworks (Jaysson et al., 2018). Due to the operational inefficiencies of the centralised method, which are characterised by poor performance, and inefficient resource utilisation, consumers and small-scale energy producers have suffered immensely (Naiyu et al., 2019). Traditional energy markets face several significant problems, including:

- Centralized Control: Utility companies and energy exchanges have control over energy trading systems. This aspect results in a closed market, minimal competition, and a lack of market transparency. Besides, energy trading participants have limited diversity, and the centralized control determines participants' flexibility
- Intermediaries and High Transaction Costs: Energy transactions involve numerous people, such as brokers, traders, and regulators. These people make already complex energy trading processes even more challenging. Energy trading systems have additional procedures, compliance requirements, and documentation. These features increase transaction costs and paperwork complexity. Therefore, small energy producers and consumers experience difficulties in trading, since the complexity delays each transaction.
- Lack of Transparency: The traditional energy trading ecosystem is often plagued by lack of transparency. Without reliable access to the most current data regarding energy sources, market prices, or carbon-free energy origins, participants may confront mistrust and misinformation.
- Inefficient Settlement: Settlement of energy processing is time-consuming and complicated. It may take many working days to settle after the completion of the purchase. Settling after the deadline increases financial risk and disrupts the optimal function of the market.
- Limited Access for Small Producers and Consumers: The traditional energy system mainly favors large energy producers and consumers, households that have installed solar panels have no active role in energy trading.

Unlike conventional systems where a single organization takes responsibility for managing data and transactions, a blockchain system operates in a different manner. To allow the computing nodes to work together to validate and record transactions, a consensus algorithm is needed. Because the system operates without intermediaries and is hence more transparent, the use of this system has become increasingly popular due to its capacity to address significant concerns in the energy trading sector (Athira et al., 2022). Blockchain is a significant development for Peer to Peer (P2P) energy trading. It implies that energy providers and consumers may trade energy directly without engaging large middlemen or utility companies (Shen et al., 2019). A contract based blockchain is termed a smart contract, and it's a computer protocol that can automatically execute a task. It allows the energy to be automatically transacted between the concerned parties according to a prior agreement (Shuai et al., 2019). Thus, it helps larger groups of individuals and communities participate in energy trading, leading to a more sustainable and equitable energy market (Aparna et al., 2023).

The security and sustainability of energy transactions are reaffirmed by the blockchain's immutability and transparency, which also ensure that the user has confidence in the system (Athira et al., 2024). Distributed Energy Resources (DeRs) play an important role in ensuring that power supply and demand remain in total balance (Sai et al., 2024). Smart contracts governing the terms of transacting within a blockchain enable the dynamic adaptation of DERs to the ever-changing grid to improve grid resilience and energy utilization. Blockchain enables users to trade in renewable energy, therefore reducing their dependence on carbon fuels critical for reducing overall emission and increase sustainable energy.

1.2 Key features of blockchain in energy trading

The features of blockchain in energy trading are Ayman et al. (2021a):

- Settlement and Reduced Costs: Blockchain facilitates automated financial transactions and settlements by eradicating the need for intermediaries, allowing for faster settlement. Blockchain manages and reduces the administrative burden associated with conventional energy trading systems and minimizes settlement times.
- Renewable Energy Certificates: Blockchain technology can be used to make and track Guarantees of Origin and Renewable Energy Certificates (RECs). The environmental characteristics of electricity generation produced from renewable sources are represented by digital certificates, which can be swapped on blockchain networks. It assures the safety and transparency of these certificates and promotes the sustainability of trust in the green energy market.

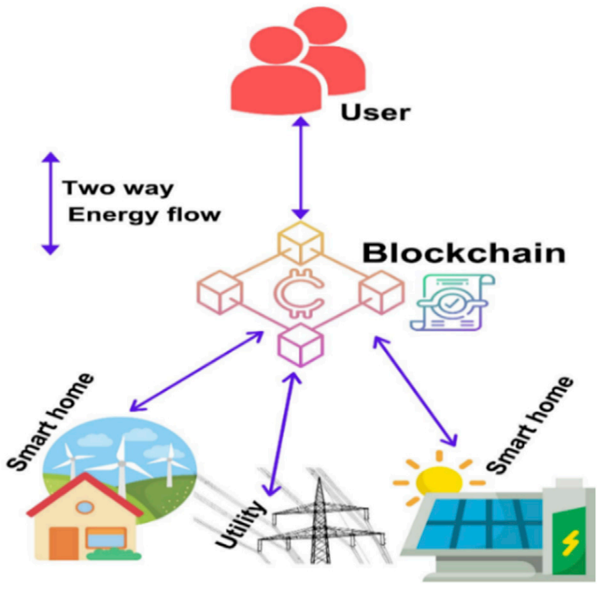

FIGURE 1
Blockchain technology process for energy trading.

- Grid Management and Energy Balancing: The technology allows for grid management as well, helping maintain the energy balance due to the real-time data exchange of buyers/sellers, stakeholders in energy transactions, and the market operator. It supports the integration of DERs into the grid. In particular, together with IoT devices, sensors, and smart meters, the developers indicate the possibilities to monitor key metrics to optimize energy distribution. Similarly, blockchain helps P2P sharing in microgrids.
- Energy Supply Chain Management: Blockchain technology can enhance the transparency of energy supply chains. This technology is designed to monitor and analyze all stages and aspects of the energy supply chain: from production sources to consumption endpoints. As a result, blockchain technology ensures a reduced level of fraud and better supply chain visibility.
- Energy Billing and Settlement: Blockchain's automated transaction verification and validation can be used to streamline and optimize energy billing and settlement. By allowing transactions based on pre-set rules, smart contracts simplify and automate the administrative process.
- Electric Vehicle Charging and Billing: Blockchain technology streamlines and secures transactions within the electric vehicle (EV) charging infrastructure. It ensures transparent billing and settlement, authenticates charging stations, and promotes charging network interoperability, making it easier for EV owners and encouraging the expansion of e-mobility.

Numerous blockchain platforms have emerged each with unique features (Vahid et al., 2021). These platforms are the basis for the foundation for creating decentralized applications (DApps) in various industries (Kaidong et al., 2021), like energy trading, healthcare, supply chain management, finance, etc.

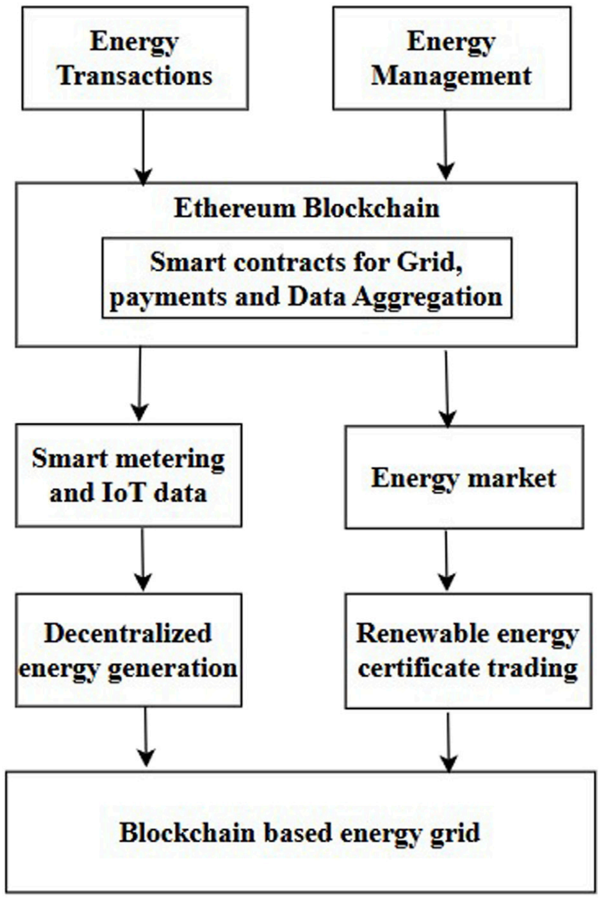

FIGURE 2
Application of Ethereum blockchain in the energy sector.

Figure 1 illustrates an application of blockchain technology in energy trading. Consumers are becoming prosumers due to the widespread installation of renewable energy systems such as solar panels and wind turbines because of their affordability. By integrating blockchain technology into the user interface/user experience (UI/UX), end users can utilize smart home data for energy trading and monitoring demand response. This smart home data includes details on energy consumption patterns, appliance usage, and renewable energy generation (Ante et al., 2021; Yahia et al., 2021; Son et al., 2021). This comprehensive analysis highlights the key characteristics of prominent blockchain systems utilised in energy trading.

2 Literature review

Ethereum and Hyperledger Fabric's performance as private blockchain systems in the context of private deployments is another area of analysis (Ahmed et al., 2020). The evaluation reviewed the scalability and limitations of the private blockchain platforms. Apparently, Hyperledger Fabric outperforms Ethereum in the required time for completion of execution, latency, and throughput. For instance, a study (Nasrin and Zahir, 2020) has evaluated the Ethereum blockchain and double auction system usage

TABLE 1 Popular blockchain pilot projects in the power sector.

Entity/Project	Location	Description
UPPCL and UPNEDA P2P Trading Pilot	India	A pilot project in Uttar Pradesh state allowing direct energy trading between government buildings with solar panels
Tata Power's Solar Energy Trading Project	India	A P2P solar energy trading initiative using blockchain technology
Grid Exchange Project	Canada	A blockchain-based platform enabling energy exchange between utilities and consumers, promoting local P2P energy trading
TraceX	United States	A digital marketplace for trading RECs, integrated with Midwest Renewable energy Tracking System (M-RETS)
Brooklyn Microgrid	United States	A microgrid pilot in Brooklyn facilitating P2P energy trading among residents with solar panels

for creating and assessing the energy trade on a local electricity market. The researchers have reported that Ethereum could support a lot of transactions by interacting with the chain consistently and fast.

The topics include the secure, access, private, and scalable functions of the blockchain (Victor and Hossain, 2019). Blockchain is secure as a result of a tamper-resistant method to record transactions. This way of transaction recording makes it a perfect application for supply chain management and financial transactions, which need trust. Cryptographic techniques used in the blockchain ensure security by giving pseudonyms to the data, and thus protect data confidentiality. Blockchain scalability is challenging owing to the requirement to improve transaction capacity in both throughput and transaction time. Regular research is conducted to enhance and optimize the platforms to accommodate user's demands. Some of the private blockchain platforms are Ethereum, quorum, corda, and hyper ledger fabric, which stack regularly assessed for their scalability and performance (Chinmay and Siddharth, 2018).

Pricing systems applicable to energy pricing and network service pricing for P2P was analyzed. Some conflict of interest in network service pricing was discovered that may inhibit agents participation in the market (Hyun et al., 2023; Wayes et al., 2021; Yuekuan and Peter, 2023). The combination of Hypertext Transfer Protocol (HTTP), blockchain technology, and the Internet of Things (IoT) can make the system more effective in trading energy among the participants (Mirza et al., 2022).

Researchers conducted comparative studies on several blockchain development platforms to help organizations overcome the challenge of selecting the appropriate platform for secure and transparent transactions (Ayman et al., 2021b; Tarek et al., 2022; Chao-Qun et al., 2024). Developers need to choose the platform that meets their specific requirements, as not all platforms meet the standards of every organization.

The integration of edge computing and blockchain technologies has been a recent highlight for Unmanned Aerial Vehicle (UAV) systems; offers key solutions for challenges such as privacy, security, and efficiency (Yao et al., 2024a; Yao et al., 2024b; Dong et al., 2021; Yao et al., 2021). To address the biometric privacy concerns, frameworks were introduced to localize sensitive information to edge devices to ensure secure location data collection. Systems based on blockchain self-sovereign identity (Dong et al., 2021) have been developed to allow security identity management, as well as the power of controlling sensitive data to be transferred over to the user. Moreover, the incorporation of real-time threat detection and advanced authentication protocols in security frameworks have strengthened the cyber resilience of UAV systems (Yao et al., 2021). To overcome non-IID data problems in UAV logistics, federated learning frameworks have also been proposed (Carlos et al., 2022), where data can be processed without compromising individual privacy. This shows how blockchain and edge computing can be used to improve UAV systems for energy trading and logistics.

According to the literature study, numerous research have been carried out to compare blockchain platforms, but they have only taken a limited number of platforms into consideration. The goal of this study was to analyse popular blockchain platforms in-depth. Instead of focusing on a small number, the study tried to cover as many well-known blockchain platforms as it could in our research.

3 Methodology

A systematic procedure was adopted to analyze the blockchain platforms. The analysis targets the popularity of the platforms in the market, technological advancement, and the adoption of the technology in the industry. The data for the analysis was collected from sources such as academic research, industry reports, and the platforms' official documentation. Predefined criteria, including energy use in the platform, consensus mechanism, transaction processing rate, platforms' security, scalability solutions, strategies for mitigating cyberattacks, privacy-preserving mechanisms, regulatory considerations, the integration of artificial intelligence for platform optimization and availability, were used to analyze each platform. The selected criteria enable the identification of the principal strengths and weaknesses of the platforms in the context of energy trading and management. A broad range will be considered to enable the development of a comprehensive understanding of the performance of known platforms and their viability in energy trading and management processes. Hence, the study aims to provide an elaborate understanding of popular platforms' ability to support or execute energy trading and management using the provided features.

The following sections will analyze different blockchain platforms in the context of energy trading. Each platform will be examined to highlight its features, strengths, and applications in the energy sector.

TABLE 2 Comparison of different blockchain platforms.

Blockchain platform	Consensus	Transaction speed	Availability	Energy efficiency	Scalability solutions	Cyber mitigation techniques	Privacy-preserving techniques	Use cases
Ethereum (ETH)	Proof of Stake (PoS)	Moderate	High	Moderate	Layer 2, roll-ups, sharding	Smart contract audits, network activity monitoring	ZK-SNARKs, off-chain data storage	Energy trading, smart contracts, decentralized applications (DApps)
Hyperledger Fabric	Practical Byzantine Fault Tolerance (PBFT)	High	High	High	Parallel transaction processing, sharding	cryptographic security, multi-signature-system	Channels, ZKPs	Enterprise solutions, supply chain, identity management, Energy sector
Power Ledger	Custom consensus	High	High	High	Dual layer blockchain system	Two tier blockchain system, AI powered anomal detection	Anonymization layers, data obfuscation	P2P energy trading, renewable energy certificates
LO3 Energy	Custom consensus (Exergy)	High	High	High	Localized specific sub-networks, AI transaction batching, predictive load balancing algorithms	quantum-resistant cryptographic algorithms, geo-restricted nodes, behavioral analytics, firewalls	Ring signatures, Selective disclosure mechanisms, Namespace-based access control	Local energy marketplaces, microgrids
Energy Web Chain	Proof of Authority (PoA)	High	High	High	Layer-2 solutions, AI-Timestamped transaction	Dynamic node rotation, firewalls, AI-enabled anomaly detection	Energy token cloaking, ZKP's, localized private sub-networks	Decentralized energy applications, carbon credits
Bitcoin Cash (BCH)	Proof of Work (PoW)	Low	High	Moderate	Lightning Network	multi-signature wallets, cryptographic encryption and routine audits	ZKPs, CoinJoin, Stealth addresses	Digital cash, P2P transactions
Stellar Lumens (XLM)	Federated Byzantine Agreement (FBA)	High	High	High	Stellar Consensus Protocol, Channels, sharding	multi-signature wallets, cryptographic encryption and network monitoring tools	ZKPs	Cross-border payments, remittances
Litecoin (LTC)	Proof of Work (PoW)	High	High	Moderate	Lightning network, off-chain, state channels, rollups	cryptographic encryption, multi-signature wallets, network monitoring systems, two-factor authentication	ZKPs, MWEB	Digital silver, fast transactions
Polkadot (DOT)	Nominated Proof of Stake (NPoS)	High	High	High	Sharding, Cross-Chain Message Passing, decoupling execution and offloading	Parachain isolation, adaptive load balancing, parachain slot auctions	Baseline batch ring signatures, ZKPs, stealth addresses, Data Selective Disclosures	Interoperability, parachains
Dogecoin (DOGE)	Proof of Work (PoW)	High	High	Moderate	Layer-2, merged mining, transaction compression	Green staked mining, adaptive difficulty adjustments, merged mining	ZKPs, stealth addresses, ring signatures, homomorphic encryption, metadata obfuscation	Fun and tipping, low fees

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TABLE 2 (*Continued*) Comparison of different blockchain platforms.

Blockchain platform	Consensus	Transaction speed	Availability	Energy efficiency	Scalability solutions	Cyber mitigation techniques	Privacy-preserving techniques	Use cases
DeSo (DESO)	Custom consensus (PoW)	High	High	High	Dynamic node specialization, AI-enabled scalability optimizers, hierarchical sharding and batching algorithms	ZKPs, E2E data Encryption, Decentralized identity, AI-powered smart contracts, hardware security modules	Decentralized identity, confidential transactions, ZKPs	Social media, creator coins
NEM (XEM)	Proof of Importance (PoI)	High	High	High	Custom mosaics, AI-assisted load balancing, microtransaction aggregation	Multi-layer authentication, bridge audits, geo-restricted nodes	Encrypted mosaics, namespace-based access control, multi-layer data masking	Supply chain, asset tracking
ALGORAND (ALGO)	Pure Proof of Stake (PPoS)	Very high	High	High	Energy transaction batching, adaptive fee structuring, Layer-2, state channels	PPoS, quantum-repellent signature, auditing software	Layer-1 permissions, ZKPs	Financial applications, DeFi
Solana (SOL)	Proof of History (PoH) and Proof of Stake (PoS)	Very high	High	High	The Turbine protocol, Gulf Stream prefetches, Cloudbreak	Dynamic validator reputation systems, AI-based anomaly detection systems	Sealevel, private smart contracts	High-performance DApps, DeFi
Cardano (ADA)	Ouroboros (PoS)	High	High	High	Layer-2 Hydra protocol, Extended UTXO	stake pool saturation limit, verification of smart contracts	Mithril protocol, MPC	Smart contracts, scalability

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4 Blockchain platforms

4.1 Ethereum

One of the widely used blockchain platforms is Ethereum. It allows creating smart contracts and decentralized applications (DApps) (Marc, 2019; Vitalik, 2013). While Ethereum was not developed explicitly for the energy trading sphere, due to its programming abilities and availability it's now one of the popular blockchain platforms used in the energy sector (Francesco et al., 2023). Indeed, one of the main features of Ethereum is that it supports smart contracts. Smart contracts can be used to execute automated transactions among the prosumers and participants in the energy network.

In contrast, Ethereum, being decentralized, avoids such intermediaries and also makes energy trading among peers simpler. Indeed, producers can create a token and develop digital assets based on the Ethereum blockchain (Sidharth and Aarthi, 2023). These tokens refer to a certain amount of energy or a share in a renewable energy project. Consumers can acquire these tokens from producers, making the energy trading transparent and available for all the participants. The Ethereum blockchain platform is an open platform that offers abundant development tools, libraries, and other related resources, such as documentation, tutorials, forums, and community support. The ecosystem allows the development of user-friendly energy trading apps with enhanced features and functions.

Ethereum also has some limitations. Scalability is one of them. It experiences scalability problems, particularly when the network is busy, which leads to higher transaction costs and slow response (Athira et al., 2023). Ethereum 1.0 migrated to Ethereum 2.0 to address this issue. Ethereum 2.0 uses a different consensus model called Proof of Stake (PoS) instead of the Proof of Work algorithm of earlier systems. PoS works by selecting a validator based on the amount of cryptocurrency they are holding and willing to stake. The participants who have a higher number of stakes will be the validators, who are responsible for creating and validating transactions (Jae et al., 2021). Ethereum 2.0 transitions improve scalability, energy consumption, and security.

Ethereum is an excellent choice for energy trading, as it offers the most flexibility and programmability. Ethereum supports creating smart contracts and DApp development. Ethereum provides Layer 2 solutions such as Optimistic Rollups and zk-Rollups to improve its scalability which relieves the network congestion by offloading transaction processing from the Ethereum main chain. Also, an Ethereum 2.0 sharding mechanism will break the network into smaller parts so that it can handle transaction volumes at a high rate (Honari et al., 2022).

The implementation of Ethereum technology in the energy sector is shown in Figure 2. Ethereum blockchain technology can securely record and process energy transactions. This is done through smart contracts programming, which, in turn, controls the payment, collects the necessary data, and maintains the grid. The integration of smart metering and IoT devices allows for monitoring consumption and generation in real time. One of the key advantages of using the Ethereum platform is the possibility to integrate decentralized generation, including renewables, into the grid. This technology also allows for direct market trading between peers, and Renewable Energy Certificates (RECs) may be generated and traded in the energy market. Additionally, the transparency of Ethereum also enables privacy-preserving methods in particular zero Knowledge proofs (ZK-SNARKs) and off-chain storage to safeguard data and anonymize sensitive energy usage data (Valadares et al., 2023).

Although cryptographic techniques and multi-signature wallets provide the utmost degree of protection, the blockchain is prone to various attacks: 51% attacks, smart contract hacks, and denial-of-service (DoS) attacks. In order to mitigate these vulnerabilities, regular smart contract audits, secured private keys, and network activity monitoring will be required to maintain the integrity of blockchain-based energy systems. In addition, regulatory frameworks for energy trading differ from country to country and since Ethereum is a global platform, Ethereum-based platforms should also comply with data protection regulations such as that of EU GDPR to make privacy possible. The flexibility of Ethereum which highlights its ability to comply with these region-based energy market rules further enables smoother blockchain integration in the energy.

Integrating Artificial Intelligence (AI) with Ethereum-based energy platforms improves predictive energy management. AI supports analyzing real-time data from smart meters and IoT devices, making predictions on energy consumption patterns, and optimizing energy distribution from renewable sources. Smart contracts powered by AI can facilitate the automatic execution of energy transactions, enhance system efficiency, and support demand-response initiatives.

4.2 Hyperledger fabric

Hyperledger Fabric is an efficient and secure intelligent energy trading solution that is primarily developed for business applications and has a variety of features and capabilities (Carlos et al., 2022). Hyperledger Fabric is permissioned blockchain, that is participants in the network are authenticated. Permissioned network is crucial in the energy trade because the network contains only validated participants such as suppliers, customers, and regulators. Which will enhance compliance, protection, and confidentiality.

The Hyperledger Fabric framework enables high performance and scalability. The platform divides transaction processing into separate components, including ordering service, endorsement, and validation. The fabric design supports scalability solutions like parallel transaction processing and sharding, making it appropriate for large energy trading networks with huge transaction volumes. The Hyperledger enables simultaneous execution and efficient resource utilisation which is required to handle large amounts of data flow from millions of prosumers. Within the blockchain network, it facilitates the development of private subnetworks called channels. Channels can be formed in energy trading to enable private transactions between particular participants. The channels ensure that sensitive information, such as energy prices or consumption data, is only shared with the relevant parties. It is facilitated by various privacy-preserving mechanisms and can be further improved through Zero Knowledge Proofs (ZKPs) without disclosing sensitive information (Magda and Manolis, 2021; Yonghyun et al., 2020). Through a channel, network administrators can specify roles, rights, and access policies for each user, ensuring that only authenticated users authorized by the blockchain network can access it. This feature improves security and trust among participants. These layers of control protect against exposure to cyberattacks that could affect energy trading process. Through a cryptographic security and multi-signature-based validation system, as well as a network monitoring process, the system finds better protection from any unauthorized access or malicious attempt.

Chaincode is a concept of smart contract used to develop business logic and automate procedures in energy trading in Hyperledger Fabric. The smart contracts make it easier for the parties to define and fulfill their legal obligations as well as resolve any of the disputes without the need for a court of law. Chaincode is highly suited to the software development requirements because it can be implemented using various programming languages, such as Go, JavaScript, and Java. Interoperability is one of the main characteristics of Hyperledger Fabric. It can easily connect with energy management systems, IoT tools, and data sources. Hyperledger Fabric provides an option to choose a consensus process (for example, Raft or Practical Byzantine Fault Tolerance (PBFT) to ensure secure validation of transactions). It guarantees uniformity and transparency in energy trading transactions across the ecosystem, regardless of network composition (Sidharth and Aarthi, 2023). Hyperledger PoS consensus, its scalability features, and its privacy-preserving mechanisms can be complementary in providing hyperledger based systems to seamlessly accommodate rapidly evolving regulations in diverse regions. Such frameworks govern some aspects including carbon footprint tracking, data privacy, or certification of renewable energy.

Finally, the involvement of AI on blockchain-based predictive energy management is one of the most important use cases. AI analyses smart meter and IoT device data to predict demand and optimize supply and distribution of energy using machine learning algorithms and data analytics. By implementing this, it enables blockchain-based energy trading systems to automatically increase and decrease the flows of energy to the network based on consumption forecasts, as smart contracts would ensure the execution of energy transactions. AI-enhanced predictive systems are critical to 24/7 energy transaction management as well as grid stability in decentralized energy markets.

4.3 Bitcoin cash (BCH)

Bitcoin Cash (BCH) is a digital currency that shares numerous similarities with Bitcoin while incorporating distinctive features (Wenyu et al., 2020). BCH is categorized as a fork of Bitcoin, although supporters claim that BCH is more in line with the original concept of Bitcoin. The Bitcoin Cash protocol ensures that the total number of coins in circulation will never exceed 21 million (Cash). BCH provides heightened privacy and anonymity compared to conventional payment systems.

BCH furnishes participants with full control over their money, besides global accessibility. Many businesses encourage the usage of BCH by discount offers, as it avoids credit card fees and promotes the use of this new payment system. The features are highlighted below.

(1) Optimized Energy Transactions: BCH is secure and decentralized platform brings energy transaction to a new level by allowing P2P energy trading in seconds. BCH has scalability limitations, which could limit its ability to process high transaction volume. Layer-2 processes or off-chain scaling solutions, e.g., Lightning Network, would need to be used for high-volume, high-speed energy transactions across lots of thousands of users.
(2) Renewable Energy Adoption: The BCH blockchain further supports the integration of DERs into energy markets by enabling transparent and secure transactions. The latter presents a path of energy providers that incentivizes businesses and users to choose green options and develop sustainable worlds of energy. Certain privacy-preserving techniques, ZKPs can be embedded in BCH to process transactions (e.g., consumption patterns, prices of energy, etc.) to remain private in the exchange and certification process. Additionally, CoinJoin, mixes many transactions to provide privacy in the system. With stealth addresses, create an address for every transaction, hiding the identities of participants and the transaction details. In addition, Schnorr signatures, which BCH already supports, can aggregate signatures to reduce transaction size and enhance privacy.
(3) Enhanced Transparency and Security: Bitcoin Cash make energy transactions easily traceable and accountable on their blockchain. Such transparency padlocks security and improves efficiency and confidence among the participants. Secondly, the security features of blockchain technology help prevent fraud and ensure the accuracy of data and processes in the energy sector. Nonetheless, energy networks on BCH still require cybersecurity mechanisms including multi-signature wallets, cryptographic encryption and routine audits against threats like 51% attacks and DoS attacks. Coupled with real-time monitoring systems, blockchain can identify any possible threats at early stages and trigger an automated security mechanism.
(4) Reduced Transaction Costs: The BCH blockchain's decentralized architecture leads to a decrease in transaction fees by eliminating the need for middlemen and thereby energy trading will be more accessible and affordable for small-scale energy producers and consumers. Furthermore, it increases market participation, leading to a dynamic energy market. Energy trading based on BCH is subject to research and compliance with regional regulatory frameworks mapping the relevant energy trading, data privacy, and emissions footprints. By using smart contracts, BCH could assist companies in automating compliance with such regulations (e.g., carbon credit trading or renewable energy certifications).

A BCH-based platform could add AI-enabled predictive energy management, using data from smart meters and IoT devices in real time. Artificial intelligence can forecast when and how much energy will be used, enabling more efficient allocate Renewable energy sources and even automating trading decisions based on real-time demand and supply.

4.4 Stellar lumens (XLM)

Compared to conventional blockchain systems, Stellar Lumens (XLM) enables developers to build customer interfaces with the look and feel of real-world finance operations rather than virtual currency. The efficiency, cost-effectiveness, and processing speed of Stellar make it especially noteworthy (Hyeonoh et al., 2023; Nida et al., 2019; Pawan et al., 2023).

The importance of Stellar Lumens blockchain in the energy sector are:

(1) Efficient Energy Transactions: The XLM is a robust system for people to trade energy safely and efficiently. As the technology enables secure and fast transactions in energy trading processes, it reduces operating costs. As energy markets aggregate millions of customers and 24/7 real time transactions, Stellar faces scaling challenge. The underlying protocol is known as the Stellar Consensus Protocol (SCP) which provides fast transaction finality, and Layer-2 solutions such as channels or sharding may be necessary for high-frequency energy markets to reduce network congestion and accommodate the higher transaction throughput. Such solutions can allow Stellar to process enhanced energy transactions on a larger scale, resulting in a higher market capacity.
(2) Integration of Renewable Energy: XLM's encourages the use of renewable energy sources for energy trading process thereby promoting sustainable energy practices. Energy transactions involve sensitive data and could benefit from the implementation of privacy-preserving techniques such as ZKPs on Stellar's blockchain making sure that personal energy consumption data stays private while still maintaining transparency and validation of the source and provenance of energy traded.
(3) Cost-effective transactions: As XLM is a decentralized ledger, it allows for effective cost-reducing transactions that lower the participation costs of the energy market to enable a more efficient and active market. However, decentralized platforms like Stellar are still susceptible to cyber threats, including 51% attacks, smart contract weaknesses, and network outages. While Stellar addresses these risks through its consensus model, other safety elements, such as multi-signature wallets, cryptographic encryption and network monitoring tools, are necessary to protect energy transactions. Frequent security audits and real-time threat detection will minimize disruptions and preserve the integrity of the system.
(4) Enhanced Transparency and Security: The XLM blockchain is reliable and secure. XLM ensures immutability for all energy transactions, thereby providing secure and transparent energy records. The technology already possesses remarkable transparency and security features to promote compliance with energy regulations, although most of these standards are still being drafted and the broader regulatory landscape for cryptocurrencies and blockchain in energy markets is evolving. Governments and regulatory bodies need to clarify the legal status of blockchain deployment within energy trading platforms, particularly concerning issues such as data privacy, carbon credit trading, and energy certification.

By integrating AI with Stellar, energy trading platforms can intuitively forecast energy needs, automatically allocate resources and optimize energy trading on the platform, eliminating human intervention. By processing real-time data from smart meters, AI can offer actionable insights that improve energy market dynamics, and predictive energy management, and demand-response optimization.

4.5 Litecoin (LTC)

Litecoin (LTC), is a blockchain platform in the energy industry, which is an open-source, decentralized payment network. LTC trading network allows global trading at a low cost. The LTC network is secure and provides users the capacity to monitor their financial operations. Litecoin provides higher storage efficiency and faster transaction validation times than other prominent blockchain platforms (Strepparava et al., 2022; Khaoula, 2021; Padmavathi and Suresh, 2019).

The Significance of Litecoin in the energy sector are:

(1) Streamlined Energy Transactions: LTC blockchain improves the efficiency of energy transactions through secure and simplified P2P energy trading. LTC blockchain can transact fast, thereby time and cost for trading can be reduced. Although Litecoin provides faster transaction times, scalability challenges could still pose obstacles to mass adoption of Litecoin in energy markets, particularly as transaction volume increases. Layer-2 scaling solutions, such as the Lightning Network, and processing off-chain, could be used to mitigate scalability issue. This solution will allow Litecoin to scale to settle millions of transactions per day across DERs and IoT devices. State channels serve as an excellent, practical solution to facilitate a series of microtransactions off the chain between energy producers and consumers, and settle the final state on the chain. Another way to ease scalability is to use rollups, where transactions are bundled,thereby reducing the main chain load.
(2) Renewable Energy Integration: Litecoin blockchain facilitates renewable energy integration and incentivize environmentally friendly energy-based sources.
(3) Enhanced Transparency and Security: Litecoin blockchain increases transparency and security, ensuring that participants in the energy system network. LTC's systems ensure that every energy activity is secure, immutable and reliable. For sensitive transaction data, it is important that the user does not expose his usage profile as this information could be used against him, thus, it would be good to integrate ZKPs with Litecoin so we can have secured data while being able to prove you have sent a transaction. Litecoin's MimbleWimble Extension Block (MWEB) for confidential transactions also brings its own level of privacy for the involved parties.

Despite its decentralization, Litecoin still suffers from cyber security risks such as 51% attacks, smart contract vulnerabilities, Denial-of-Service (DoS) attacks, Sybil attacks, replay attacks, wallet attacks, etc. The risk could be reduced through cryptographic encryption, multi-signature wallets and network monitoring systems to identify breaches before they happen. Other strategies like DDoS protection, Sybil attack resistance, and two-factor authentication for wallet security should also be implemented. Smart contract audits, on time security checking, and blockchain analytics can prevent vulnerabilities. Post-quantum cryptography and strong incident response plans will at the same time protect the integrity of the network.

(4) Reduced Transaction Costs: Litecoin's decentralization characteristic leads to reduced transaction costs on LTC blockchain. The reduced costs make it possible for many people to trade and manage energy in the market. Litecoin based energy trading platforms must be comply with regional regulatory frameworks covering a number of areas including data privacy, emissions tracking and trade, and consumer protection. Litecoin can also automate compliance with carbon credit trading or renewable energy certification processes, by integrating smart contracts. Platforms also need to comply with a broad span of global data protection regulations such as GDPR as well as anti-money laundering (AML) and know your customer (KYC) regimes, in addition to standardized environmental reporting frameworks. Dealing with trade policies, tariffs, and standards for interoperability, cross border energy trading will need to be managed.

The transformative role of AI and Blockchain-based energy systems will enhance optimisation capability for energy distribution, predictive management, and intelligent decision making. AI can also analyze real-time data from smart meters and IoT devices using machine learning algorithms and data analytics to predict energy demand, optimize supply from renewable sources, and minimize energy waste. It assists with peer-to-peer energy trading, enhances grid stability, and consumer specific customized energy solutions through consumer behaviour analysis. Compliance management is regulated by AI systems, energy storage and management is improved to cut down on greenhouse gas emissions, and cyber security is enhanced through real-time threat-behaviour monitoring by AI systems.

4.6 Polkadot

Polkadot is a multi-chain network that promotes collaboration among several blockchains. The Polkadot provides a framework that allows disparate blockchains, called parachains, to attach to the Polkadot relay chain and link with one another (Hanaa et al., 2022). This connectivity would allow energy-related blockchains to work together more swiftly and conveniently exchange and share data to improve system integration. Polkadot is extremely scalable, which is critical as blockchain-based energy applications expand. As the number of blockchain transactions grows, Polkadot increases capacity to maintain up with the rise in transactions.

The importance and benefits of Polkadot in the energy sector are:

- Polkadot's scalable and flexible nature support energy-efficient grid by integrating green energy sources, which will enable the ability to engage in peer-to-peer energy trade. Polkadot can scale up simply by connecting new parachains (i.e., energy blockchains) to the Polkadot relay chain, each processing its own transactions in parallel with high throughput as energy markets expand and the number of energy transactions explodes. This sharding allows for the parallel processing of transactions, thereby providing the ability to handle the real time processing of high-volume energy data from millions of Smart Meters and IoT devices efficiently. The Cross-Chain Message Passing (XCMP) feature, which enables parachains on Polkadot to communicate with one another, can further boost scalability and coordination between chains. By decoupling execution from validation and offloading most workloads from on-chain nodes to off-chain collator nodes, it allows transaction throughput to be significantly optimized. It can dynamically scale and evolve to support the growing decentralized energy market as Polkadot's adaptive resource allocation and upgradable framework.
- Polkadot's security features would secure all crucial energy-related data, which would be essential in ensuring secure energy transactions. While it minimizes risk through shared security, its unique architecture means inherent risks too, such as cross-parachain vulnerabilities (malicious behaviour on one parachain affecting others), relay chain overload (the relay chain is only capable of supporting a limited amount of activity across parachains), parachain slot auction manipulation (potentially leading to stale bids not being processed, or competition-driven bidding for parachain slots) and bridge exploits. Polkadot can reduce these by utilizing parachain isolation to ensure problems on one chain do not disrupt the others as well as improving Cross-Chain Message Passing (XCMP) to better secure inter-parachain communication. The relay chain will do adaptive load balancing for scaling, and parachain slot auctions based on cryptographic proofs to keep it transparent. To secure cross-chain transactions, protect against distort or attacks, bridge security audits must be performed regularly, and also smart contracts must be secure in Polkadot-based energy trading platforms.
- Polkadot's interoperation would enhance communication among the various energy blockchains. Energy trading platforms need to ensure the privacy of consumer and energy transaction data, e.g., a combination of partially encrypted data with baseline batch ring signatures on the parachains to maintain the required transparency for auditing and certification. Solutions such as ZKPs can prove data while keeping sensitive information hidden from any of the parties involved. In addition, it can obscure transaction data and enhance user privacy through components such as confidential transactions, stealth

addresses, and off-chain data storage. Data Selective Disclosures and homomorphic encryption allow data to be shared autonomously by consumers and at the same time analytics and certification processes can take place without revealing personal data.

Polkadot has numerous limitations. First, the complex management will slow down too many decision-making processes and create an environment where numerous participants on the energy trading will be dissatisfied. Furthermore, developers would find it hard to adjust to this radically new platform and ensure that the blockchain can interact with each other. Finally, the cost and difficulties of running a node may significantly reduce the scope of people genuinely interested in joining the network. While a permissionless blockchain like Polkadot may enable new types of market structure in the energy domain, regulatory uncertainty may be a barrier to adoption unless platforms can compensate as per energy laws, sustainability initiatives and data protection regulations. Parachains based on Polkadot needs to be able to comply with regional energy trading policies, frameworks for renewable energy certification, and carbon emission reporting requirements to comply with global sustainability goals. It must comply with privacy laws, cybersecurity standards, and tokenization regulations pertaining to sensitive consumer information, energy tokens, and carbon credits. Polkadot also has to overcome cross-border energy trade complications and work on supporting standardization and thus reducing friction with established energy systems.

Due to Polkadot's architecture it enables the integration of AI with the blockchain. Predictions powered by AI, can help to optimise the XCMP component. AI-powered dynamic resource allocation can balance the workloads and enhances scalability and prevent the multi-chain network congestion across the parachains. In addition, AI systems can also used to stabilize decentralized energy grids, predict collator node maintainence as well as automate regulatory compliance. Custom AI models for a specific use case (i.e., renewable energy certification or carbon credit tracking) on individual parachains and advanced AI-assisted token pricing will guarantee optimal market prices of tokens in energy markets.

4.7 Dogecoin

Based on the Litecoin protocol, Dogecoin cryptocurrency employs a PoW mining algorithm, where miners vie to solve intricate mathematical problems to validate transactions and earn rewards in return (Nagamani et al., 2021). The intensive energy consumption associated with Dogecoin mining triggers elevated concerns. According to the Digiconomist Dogecoin Energy Consumption Index, Dogecoin consumes around 0.12 kWh of energy per transaction. This is comparable to Bitcoin's energy consumption of 0.13 kWh per transaction.

The benefits of Dogecoin in the energy sector are:

(1) Micropayments: Micropayments, referring to small financial transactions usually involving very low amounts of money, can be facilitated using Dogecoin for energy payments. This approach could benefit consumers who prefer to pay for their energy consumption in real-time, allowing for greater control and transparency over their usage. Additionally, energy providers could utilize Dogecoin micropayments to reward consumers for reducing their energy consumption, promoting energy efficiency initiatives.

The fundamental scalability limitations of Dogecoin make high-frequency micropayments infeasible. The merged mining and green staked mining enhance its scalability by leveraging shared computational power, and alternative block sizes combined with transaction compression provide additional on-chain efficiency. Building a Dogecoin specific Layer-2 or dedicated micropayment channels would allow for transactions to be performed instantly and with no cost associated specific to its end use. Lightweight nodes and dynamic fee systems can increase decentralization and affordability, ensures greater decentralization and affordability, thus Dogecoin remains a feasible platform for high-frequency micropayments.

(2) Peer-to-peer energy trading: Dogecoin has the potential to support direct commercial transactions in energy between consumers. This enables individuals to buy and sell energy directly among each other, eliminating the oversight of a central intermediary. Various privacy-preserving techniques can use in Dogecoin to ensure that sensitive transaction data, including energy consumption patterns and personal information, remains confidential. ZKPs make it possible to validate energy transactions without disclosing sensitive information. More advanced mechanisms such as stealth addresses, ring signatures, and confidential transactions provide additional layers of anonymity to user identities and transaction amounts. Mixing services (CoinJoin) and off-chain transactions can hide transaction flows and add further to the privacy. Technologies such homomorphic encryption and metadata obfuscation shields sensitive data from unauthorized access.
(3) Investment in renewable energy projects: Utilization of Dogecoin for investments in renewable energy projects contribute to the creation of additional renewable energy capacity, thereby lessening dependence on fossil fuels. Dogecoin need to comply with numerous energy market regulations, including for carbon credits, renewable energy certificates and cross-border energy trading. Dogecoin can utilize smart contracts to automate its compliance by monitoring renewable energy generation, executing trades of carbon credits, and confirming compliance with local energy regulations. Also, energy units tokenizing, deploy decentralized identity (DID) systems, and permitting automated collection of taxation and fees can also help compliance easy.

Here are few instances of Dogecoin projects underway in the energy sector:

- In Australia, the Power Ledger platform utilizes Dogecoin for enabling P2P energy trading.

- The Sun Contract platform employs Dogecoin to encourage consumers' participation in renewable energy projects.
- The Grid + platform applies Dogecoin to reward consumers for lowering energy consumption.

Combining AI with Dogecoin's blockchain can transform energy management by enabling micropayment-driven energy transactions and AI-powered tipping systems for promoting energy efficiency. AI can optimize decentralized microgrid management and implement dynamic energy tokenization to simplify and enhance energy trading. Dogecoin users can benefit from gamified energy conservation and energy data monetization, with AI ensuring fair compensation and privacy.

Overall, Dogecoin is a less mature cryptocurrency than Bitcoin and Ethereum, ensued by its higher energy consumption, lower scalability, and lower adoption. However, Dogecoin has lower transaction fees.

4.8 DeSo

DeSo is a blockchain platform that uses social media to give users more control over their data and monetize their content. Albeit a platform in its early stages, DeSo holds the potential to make a substantial impact on the energy sector. DeSo could be used to create new channels for consumers to interact with energy providers and trade among each other (Nagamani et al., 2021; DeSo, 2024; Rupali et al., 2023).

The importance and benefits of DeSo in the energy sector are:

- DeSo is a secure blockchain platform that uses cryptography to protect data. This is important for the energy sector, as it needs to be able to protect sensitive customer information and energy consumption data. ZKPs allow users to verify their energy consumption without disclosing personally identifiable information (PII), enabling DeSo to store energy consumption off-chain and keep the ledger clean and secure. Further encryption on metadata, selective disclosure and ring signatures are the technology which already exist preserving user information and also supports transparency. Decentralized identity (DID) systems and confidential transactions provide secure authentication and data sharing. Advanced techniques (e.g., homomorphic encryption, on-chain data obfuscation, or privacy-enhanced Layer-2) enable scalability without compromising privacy.
- DeSo operates on a public ledger ensuring that all transactions are always accessible to the public. For the energy sector, the approach ensures that the parties investing in the sector exhibit higher discipline and transparency. DeSo's transparent ledger enables easier auditability also ensures compliance with a wide range of local and international regulations, such as carbon credits, energy certification, and data privacy laws. By integrating DID systems, DeSo ensures secure authentication and adherence to AML and KYC requirements. Smart contracts can automate compliance audits, taxation, and subsidy distribution, reducing administrative burdens and enhancing regulatory adherence. DeSo's ability to track carbon footprints and manage RECs aligns energy transactions with sustainability goals. Additionally, data localization, cross-border trade facilitation, and on-chain governance ensure that DeSo remains adaptable to evolving regulations.
- DeSo's blockchain is a highly scalable, low energy-consuming technology designed to handle many transactions safely and rapidly. Another key aspect of DeSo's scalability is making use of dynamic node specialization to process energy transactions, using state channels for IoT devices, and generating energy transaction-specific parachains to uniquely dedicate high throughout activities from the main chain. AI-enabled scalability optimizers allocate resources dynamically, while hierarchical sharding and batching algorithms reduce congestions in the network. It complements Proof-of-Storage consensus with decentralized data lakes for efficient data management and scalability.

Collaboration with energy companies, regulators, and consumer advocacy groups can reinforce trust and establish credibility. Open-source development and third-party audits can validate the platform's security and compliance. Incentivizing participation through energy credits or tokenized rewards can drive engagement, while regulatory sandboxes allow testing in controlled environments. Hosting DeSo-focused energy innovation hackathons and training programs can foster collaboration, build expertise, and create a community of advocates.

Security of DeSo will be critical in the energy domain. Decentralized identity for secure verification of participants, AI-powered smart contracts for threat detection systems could be include, in addition to traditional security systems. Also, use of ZKPs and E2E data Encryption allows security to energy-sensitive data while geo-restricted nodes, blockchain firewall provide regional and network-level protection. More complex technologies, such as abnormal behavior detection analytics, hardware security modules (HSMs) and consensus integrity monitoring help against advanced attacks.

Energy companies are concerned about the upfront costs of implementing DeSo, like building infrastructure and incorporating DeSo into existing systems of operations. Utilizing Node-as-a-Service platforms and shared node infrastructure models can help eliminate substantial hardware up-front investment. Tokenized incentives for early adoption, pay-as-you-go on blockchain services, and energy transaction subsidies will also help incentivize this transition (to make it more economical). DeSo could also allow for crowdfunded infrastructure development and blockchain-integrated financing to offer flexible funding options. Partnering with governments to secure grants and public-private partnerships, along with offering customizable APIs and education programs, ensures a smoother and cost-effective onboarding process. These strategies leverage DeSo's unique capabilities to make blockchain adoption accessible and appealing for energy providers.

4.9 NEM platform

NEM is a blockchain platform designed for ease of use and scalability. To distinguish it, it uses a different and unique proof protocol, Proof-of-Importance (PoI) (Mohammad et al., 2020), which is more energy-efficient than the commonly used mechanisms such as PoW. Additionally, NEM enables users to create custom digital assets.

The significant impact of NEM on the energy sector are:

- The invention of new energy markets and trading platforms in NEM allows producers to sell energy to end-consumers without middlemen. As energy market expands, it will be critical for the blockchain to scale to process millions of real-time energy transactions. In addition to common approaches such as sharding, Layer-2 solutions, and sidechains, NEM can make use of their PoI consensus to prioritize energy transactions as is necessary. Energy-focused sub-networks and IoT-aligned sidechains can keep high-frequency transactions separate, optimizing it, while custom mosaics present lightweight options for energy data tracking. Other innovations like dynamic block finality, AI-assisted load balancing and microtransaction aggregation provide seamless scalability. The implementation of decentralized data compression and multi-chain interoperability further propels NEM's capacity to meet the requirements of smart meters and IoT devices for millions of users.
- Demand response systems can be created using NEM. Beyond ZKPs and off-chain data storage, NEM can leverage encrypted mosaics to securely represent energy data and namespace-based access control to manage granular permissions. Techniques such as selective disclosure smart contracts and multi-layer data masking offer the capability to conduct private yet verifiable interactions, while privacy-preserving integration of IoT allows to communicate privately yet verifiably. Additional technologies such as ring signatures, AI-powered anonymization, and time-limited data exposure will ensure that these improvements are implemented without compromising system functionality and that systems are all statistically secure while keeping the level of user anonymity high.
- NEM can also be used for efficient microgrid management. Microgrids, a decentralized system that integrates small-scale alternative power sources and for the generation of electricity. To enable the integration of microgrids with existing energy markets, regulatory frameworks must be reformed, as microgrids are increasingly widespread. Innovative solutions to comply with local and international energy regulations are made possible through NEMs flexibility, PoI consensus and mosaic-based assets. Carbon emissions, renewable energy certification, and grid stability can all be governed by smart contracts. Namespaces help keep the regional compliance in check assuring inter-operability of microgrids. IoT integration allows real-time reporting of energy production and emissions, while carbon credit tokenization and audit-ready blockchain records ensure transparency and trust. Moreover, decentralized governance and smart grid integration protocols allow for dynamic regulatory updates and interoperability with existing energy systems.

Like any application in which blockchain technology is involved, cybersecurity is essential in the energy market with regards to protecting transactions and consumption data from attacks such as hacking, fraud and data breaches. The standard measures can be used, but NEM can take advantage of its special architecture for advanced protection. Existing work on PoI-based monitoring and namespace-based permissions provides control and trust, and approaches like encrypted mosaics and ring signatures protect sensitive energy data. Multi-layer authentication and bridge audits secure cross-chain interactions, preventing common vulnerabilities. Using AI-driven behavioral analytics, insider threats can be detected, and geo-restricted nodes support localized security.

The Limitations of NEM in energy sector are:

(1) Proof-of-Importance (PoI System): The PoI system is more complex than the PoW or PoS systems. This complexity is difficult for new users and developers to understand, which makes it difficult to grasp and not be able to understand and perform to take effective action and to participate in the network.
(2) Recognition and Adoption: A major drawback of NEM is its limited vogue compared to the popular Bitcoin and Ethereum blockchains. Consequently, NEM struggles to build a strong network effect, a key requirement for fair and favorable partnerships, building an active community, and creating a successful ecosystem.

By combining AI and NEM's blockchain, energy trading platforms can become more efficient, adaptive, and resilient. Dynamic pricing powered by AI ensures efficient energy usage, and namespace-based resource management organizes transactions for scalability. AI can predict grid fluctuations and execute stabilizing actions using NEM's smart contracts, while fraud detection algorithms secure energy markets. Additionally, AI-driven microgrid optimization and carbon credit management promote sustainability.

4.10 Algorand-the "green" blockchain

Blockchain turning out to be one of the most impactful technologies, notwithstanding, commoners ascribe it with a negative undertone, precipitated by the sizable energy requirements innate to Bitcoin mining. Fortunately, not all blockchain networks mandate energy-intensive mining. Algorand adopted a proactive sustainable approach to blockchain by the implementation of an eco-friendly pioneering consensus mechanism, offering green blockchain solutions (Jing and Silvio, 2019).

Algorand is an open source blockchain network that uses far less energy than the bulk of its competitors. The network is safe, fast, and multipurpose, with the ability to host DApps and a diverse range of digital assets. Some Bitcoin alternatives included the PoS method to solve the carbon footprint issue, however, their solutions sacrificed decentralization. Algorand has taken a step further, ensuring that no set of block validators ever has greater power than the rest of the token holders.

Pure Proof of Stake (PPoS) is a protocol that permits Algorand to handle the so-called Blockchain Trilemma, a situation that transpires when none of the three fundamental components of an ideal blockchain: scalability, security, and decentralization are jeopardized. Unlike PoW chains, PPoS is carbon neutral, as it obviates massive units of power. Instead, PPoS was designed from the ground up to be ecologically sustainable.

The simplistic PPoS algorithm permits any user to become a block validator by stacking the native token in the system (common in PoS blockchains). Nevertheless, at random, the PPoS protocol chooses block validators, in secret. As all users have an equal likelihood of being picked up by the algorithm, the Algorand network is completely decentralized, given that the next block validator is in the dark.

The disadvantages of Algorand in energy sector are that despite Algorand's capability to handle more than 1,000 transactions per second, emerging platforms like Solana are slated for a throughput of up to 50,000 transactions per second. The anticipated transition of Ethereum to ETH 2.0 is projected to boost transaction processing capacity to a range of (1,000-to-2,000) transactions per second.

As energy market requires a large volume of transactions, Algorand can implement subchains for energy markets, and tokenized energy units to make energy trading easier. Algorand offers energy-dedicated nodes and parallel state channels specifically for IoT devices so that high-frequency transactions are handled effectively. The instantaneous finality and the dynamic block generation enable real-time processing at peak times. The techniques included are, energy transaction batching, adaptive fee structuring, and modular Layer-2 solutions for optimizing network resources, alongside flexible routing to ensure that critical transactions are confirmed with minimum friction. These specific techniques correlate efficiently with Algorands PPoS architecture.

Strategies for Algorand Integration in the Energy Sector are:

(1) Pilot Projects: Pilot projects offer stakeholders to test Algorand under controlled conditions. They reveal significant insights about its performance and applicability to various energy use cases, advocating trust in the technology.
(2) Collaboration: It is imperative for building industry-specific standards and regulatory frameworks among energy businesses, regulatory agencies, technology suppliers, and blockchain specialists. Collaborative initiatives hasten the acceptability of blockchain technologies. Algorand has a way to uniquely enable regulators by providing the asynchronous P2P processes to automate carbon credit trading and renewable energy certification using smart contracts. Algorand Standard Assets (ASAs) can serve to tokenize energy units and carbon credits, enabling transparent and verifiable tracking. ZKPs can seal sensitive energy data while permitting secure audits, and dynamic governance protocols on Algorand can facilitate collaborative adaptation of rules for energy stakeholders and regulators. Algorand enables interoperability with customized frameworks that can streamline multi-border energy trade with region-specific namespaces enabling local compliance and maintaining innovative and decentralized energy marketplaces.
(3) Interoperability and Security: Exploration of interoperability with other blockchain platforms options assures that Algorand can effortlessly interact with legacy energy infrastructure and other blockchain platforms. This adaptability enables a gradual and seamless transition to blockchain-based solutions. Threats have to address by the Algorand blockchain platform. PPoS is a method used in Algorand, where the decentralized and random selection of validators subsequently reduces the possibility of 51% attacks. In order to prevent such flaws, platforms can use stateful smart contract auditing software to determine such vulnerabilities before deployment, employ multi-signature wallets and apply quantum-repellent signature and encryption schemes to allow greater protection for users and transactions. AI enables real-time anomaly detection systems to monitor network activity proactively to prevent DoS attacks and fraud. Moreover, Algorand fosters role-based access by establishing Layer-1 permissions and enables the verification of energy data via ZKP's, further adding to the security database layer for privacy.

4.11 LO3 energy

LO3 Energy Blockchain platform is the most modern and sophisticated system that allows and facilitates trading energy. The main aim of the LO3 Energy Blockchain platform is to create a decentralized market, available for all people and businesses, to buy and sell energy directly. This kind of selling and buying is transparent, efficient, and reliable over time. LO3 Energy introduced Exergy–a blockchain platform to support P2P energy trading (Sakineh et al., 2021). Exergy is a platform that allows a local household to simply buy or sell renewable energy from neighbor household with a single click via a smart contract. In fact, Exergy focuses on creating energy local markets and creating local community based energy trading.

Key features of the LO3 Energy blockchain platform are noted below.

(1) Peer-to-Peer Energy Trading: The platform allows direct energy exchange, without the interference of transacting intermediaries. LO3 Energy require sophisticated scalability solutions to manage growing transactional volumes. In addition to sharding, Layer-2 scaling solutions, and off-chain processing, LO3 Energy may also set up localized microgrid-specific sub-networks that optimize transaction processing within regional energy systems. Through dynamic energy tokenization, LO3 Energy can issue and trade energy units as lightweight digital assets, minimizing on-chain complexity. With AI transaction batching, several microtransactions that would be filed on-chain by the smart metering system get combined into a singular on-chain transaction and as a result, the network congestion is decreased. Moreover, predictive load balancing algorithms would also dynamically allocate network resources to high-demand regions instantaneously, thus guaranteeing unbroken

scalability. By implementing these proprietary techniques LO3 Energy is able to manage millions of energy transactions, in a cost-effective, high speed and future proof manner to meet the growing needs of a decentralized energy marketplace.

(2) Transactive Energy Management: LO3 operates on the principle of transactive energy, emphasizing localized generation and autonomous energy trading among households, providing the ability to produce, store, and trade energy easily within neighborhood confines without the influence of a larger energy grid. By applying AI integrations into LO3 Energy's platform, the use of AI will allow real-time energy optimization through predictive models that are too complex for human reasoning. AI can help to create dynamic pricing models, charging customers according to changing demand and supply conditions within the network. Using the historical energy consumption data, AI can facilitate personalized energy management plans for prosumers to encourage energy-saving and sustainability practices. AI-powered fault detection systems can discover inefficiencies or anomalies in local energy grids, improving reliability and reducing waste.

(3) Smart Contracts and Tokens: The platform uses smart contracts and tokens. Smart contracts are self-executing agreements with specific conditions and rules that automatically execute and enforce terms. The platform employs them to automatically conduct and enforce an energy transaction based on the predetermined terms. Tokens serve as digital representations of energy units, allowing programmatic and secure exchange between participants. In addition to ZKPs, LO3 Energy can improve privacy by using ring signatures to hide the source of payments and multi-layer encryption to protect energy information both at rest and during transmission. Selective disclosure mechanisms can be integrated into the platform, enabling users to disclose only relevant information to regulators or auditors by preserving the confidentiality. LO3 Energy uses privacy-preserving smart contracts to implement energy trading agreements without disclosing the underlying data. Namespace-based access control can be used in individual transactions, such that only relevant entities can access specific transaction details.

(4) Decentralized Ledger: LO3 Energy uses the blockchain-based ledger to record and store power transaction details. The information is distributed across multiple nodes on the network, ensuring transparency, immutability, and security. Each transaction is timestamped, recorded, and verified by the participants on the network. This creates a transparent, immutable, and tamper-proof record of trading activity. The system components such as smart contracts and apps used by LO3 Energy are powerful but they are vulnerable to advanced continuous and discreet cyberattacks. To minimize these threats, LO3 Energy could enable multi-signature wallets for authentication of transactions, quantum-resistant cryptographic algorithms to future-proof the encryption methods, and AI based monitoring to detect and neutralize suspicious activities. Further, the platform can roll out geo-restricted nodes to easily localize threats and use behavioral analytics to spot user behavior anomalies indicative of insider threats. Blockchain firewalls are integrated with dynamic consensus thresholds to ensure smooth operational flow and to quickly eliminate potential redundancy risks around a malfunctioning node.

(5) Energy Certification and Tracking: LO3 Energy enables the certificating of energy sources used in its platform and allows tracking its sustainability. A company can certify whether it utilizes renewable energy and trade it as using blockchain. LO3 Energy needs to not only comply with applicable regional regulations regarding renewable energy certification, carbon credits, and data privacy, but it also needs to capitalize on its focus on local microgrids and transactive energy. LO3 Energy is positioned to leverage it's peer-to-peer energy trading functionality to create localized regulatory sandboxes that allow for the testing of policies in a real-world environment and adjusting accordingly. Smart contracts adjusting rates for compliance allows the platform to facilitate dynamic energy pricing based on region-specific energy market rules. A great way to do this is in a community-driven governance model that empowers local stakeholders to have a direct influence on microgrid operations while balancing any overarching regulatory standards. Furthermore, on-demand IoT-enabled producing and consuming energy reporting and logging keeps LO3 Energy in compliance with grid stabilization protocols as well as making carbon neutral certifications.

(6) Integration with IoT and Grid Infrastructure: LO3 platform, when connected to the Internet of Things technology, allows for complete real-time monitoring, load balance, and energy sources management, made possible in energy grid infrastructure. Backed by smart meters and sensors, the platform allows for secure, accurate measurement and validation of energy usage, providing the consumer and the utility with opportunities for energy-saving.

Overall, LO3 Energy blockchain platform establishes a secure, transparent, and decentralized energy trading platform. The platform seeks to disrupt the energy industry through P2P transactions, optimal energy consumption, and promoting sustainable energy practices, designed to enhance market efficiency, and sustainability.

4.12 Energy web chain

Energy Web Chain is a blockchain designed specifically for the energy sector. It aims to enable a transition to a renewable and sustainable to carbon-neutral energy ecosystem (Energy Web), supporting the continued growth of renewables, decentralized markets, and the development of distributed energy grids. EWC blockchain functions as a public, permissioned network, which implies it is open to anyone willing to take part in. At the same time, it provides specific levels of access, which makes the EWC network secure and reliable. Proof of Authority (PoA) is the consensus mechanism utilized in EWC, which gives validation power to a limited number of validators. Those validators are primarily reputable entities well-known and approved by the

Energy web Foundation. Moreover, the EWC solution is an Energy Web Decentralized Operating System (EW-DOS), application, which implies that it ensures interoperability with the existing energy standards.

EWC can handle millions of transactions from IoT devices and smart meters leveraging its PoA consensus mechanism that allows transactions to be processed faster and with lower energy consumption in a more scalable manner. EWC could also implement energy specialized sub-networks with localized transactions that are independent of the main chain, relieving congestion on the main chain. Along its native tools, EWC can facilitate lightweight transaction schemes particular to high-frequency energy trading by embedding tokenized energy units. AI-Timestamped transaction routing can smartly prioritize essential transactions, preserving real-time feedback for power-to-grid cybersecurity. Lately, energy market Layer-2 solutions that gather microtransactions from IoT can streamline on chain activity. The integration of real-time carbon tracking and certification by carbon accounting into EWC further brings interoperability at the compliance/transaction level, making the process carbon burdens transparent and ultimately scalable.

EWC enables, digital RECs creation and administration. As digital RECs represent environmental attributes of renewable energy production, they can be transferred and sold to incentivize clean energy production. The integration of AI with EWC can revolutionize energy markets through predictive grid balancing, where AI can predict spikes in energy consumption and allocate resources throughout decentralized energy systems in real-time. AI can utilize EWC's tokenized RECs to deploy real-time automated distribution, optimizing distribution based on market conditions and carbon reduction effectiveness. AI can streamline REC markets with dynamic pricing algorithms to correlate supply and demand for green energy by creating localized price using energy production data and energy demand. Moreover, AI can enable fraudulent detection by analyzing EWC's transaction patterns, thereby ensuring the integrity of decentralized energy market. EWC platform also enabled smart contracts and DApps creation and integration. While smart contracts automate the agreement process and make it secure and transparent, DApps provide a user-friendly frontend for working with an EWC blockchain. EWC can create localized private sub-networks allowing for sensitive energy data to be processed locally and separate from the wider network while maintaining interoperability. Also, energy token cloaking is a way to obscure transaction details (RECs or carbon credits), protecting the market dynamics and preventing competitive or reputational leaks. It can also be applied to real-time IoT privacy validation, protecting sensitive energy-related data others might obtain from the smart meter while keeping specific granular consumption patterns secret. Lastly, sector-specific ZKP's establish the integrity of transactions and regulatory compliance without disclosing defined quantities related to energy generation or consumption.

EWC is built on open-source principles, promoting active collaboration among energy experts, developers, and stakeholders. Adopting role-based access on namespaces can enable EWC to boost security where it could restrict access to read/write sensitive energy data and transactions only to authorized users. Dynamic node rotation within its PoA system would mitigate the impact of attacks on validator nodes. In addition, energy derived firewalls can identify and prevent exploits aimed at the energy sector. AI-enabled anomaly detection can also prevent problems by proactively detecting irregularities, such as unusual energy transactions or unexpected network activity that could indicate fraud and insider threats. Lastly, using blockchain-based device authentication, it can be made sure that only authorized devices can interact with the network, thus securing IoT devices in decentralized energy systems.

In decentralized energy markets, the unique characteristics of EWC's energy-based PoA consensus enable it to comply with global energy regulations and help it to simplify the regulatory reporting and transaction validation process. In other words, the platform can create grid-specific regulatory namespaces, enabling localized compliance mechanisms to help ensure adherence to appropriate regional energy policies. EWC blockchain enables dynamic tokenization of carbon credits, where the value of credits changes according to the metrics of renewable energy production in real-time. Also, EWC can facilitate regulatory co-governance frameworks that integrate energy regulators as shareholders that have voting power through on-chain governance to ensure continued alignment with specific regulations. With the integration of smart REC aggregation protocols, EWC enables scaling, linking, and verification of RECs through aggregation and minimizes duplication with transparency checks. Such pioneering approaches allow EWC to harmonize the legality, sustainability, and transparency of decentralized energy markets.

4.13 Solana

Solana has great potential in the energy sector and might replace traditional energy trading platforms in the future. The P2P trading of energy, renewable certificates, and carbon credits is well supported by Solana (Solana; Zeeve). Solana's high-processing power supports the processing of many transactions, ensuring that energy trading is smooth and fast. This is achieved by the Solana blockchain, which can process at least 65,000 transactions in a second. This is important because the energy sector is flooded with multiple high-frequency traders. PoS in Solana helps to secure energy transactions and trading, making the platform secure and hard to breach. The Solana blockchain supports well all the transactions involved in energy trading, and the parties involved can follow the transactions and verify them. This eases the process of conducting energy business, and no fraud can be committed. Solana facilitates the growth of energy through the formation of decentralized energy markets, where buyers and sellers can negotiate the prices of energy and sell and buy all the energy they need.

By Solana, the energy sector can develop systems to track and trade RECs, giving prosumers the confidence that they are consuming electricity generated from renewable sources. Solana can provide the tracking and trading of carbon credits, making it easy for people to offset their greenhouse gas emissions and uphold environmental sustainability. The integration of ZKPs enables Solana for the verification and validation of transaction and energy consumption without exposing sensitive information. Sealevel runs parallel execution for privacy-preserving mechanisms such as ZKPs that ensure high efficiency under heavy network loads. Additionally, Solana supports private smart contracts that can execute secure computation, where the inputs and outputs never appear on the public ledger. Furthermore, its archivers store sensitive info like user identities or elaborate transaction details in an off-chain storage, keeping essential data on on-chain. Applications developed on the Solana are available on a decentralized basis to control and manage the power grid to ensure the supply is met with demand, and the grid remains stable. The energy sector can benefit a lot from Solana as it is efficient, accessible, and transparent.

Solana is one of the thriving novel blockchain platforms due to its capability for a high number of transactions in comparison to its peers. Proof of History (PoH) is one of its kind timestamp systems combined with the underlying system that enables optimized scalability. The PoH allows Solana to be more energy efficient by creating a historical record to prove that the transaction has already occurred. This is different from other platforms as conventional chains require proof that events were arranged in time using a synchronized clock. This means that the validators can receive and vote on the new events without having to wait for the rest to verify if the events happened first. Solana implements conventional security measures such as multi-signature wallets and cryptographic encryption, it also has specific cyber threats due to its high throughput and PoH mechanism. These include time manipulation attacks where adversaries try to interfere in the timestamping process of PoH or validator spoofing, which takes advantage of the fact that the network can be so quick to rotate validators. Solana can reduce these risks by adding tamper-proof hardware oracles to PoH oracles to increase the security of the hashing order in Solana and create a dynamic validator reputation systems to identify and exclude bad actors. Further, AI-based anomaly detection systems can track network activities and detect anomalies and rate-limiting mechanisms can prevent denial of service (DoS) attacks on validators.

The advantages of Solana in the energy sector are:

(1) High Throughput: Solana can handle up to 50,000 transactions per second, a figure that towers above many of its competing platforms. Solana is the right choice of blockchain for real time, high volume energy transaction management. It uses an innovative PoH to confirm timestamps for transactions, both in verifiable order events and continuous transactions without a delay. Solana supports parallel execution of smart contracts, maximizing resource utilization and throughput. The Turbine protocol splits blocks into tiny packets to facilitate rapid transmission between the peers and Gulf Stream prefetches transactions to the edge of the network, minimizing confirmation times and costs. Through pipelining architecture, Solana separates transaction processing into several stages and can execute these stages in parallel to each other, so it can also utilize modern multi-core processors well to process large workloads with ease. Besides, data management is efficient with Cloudbreak, which writes and reads concurrently, while archivers move old data out to lightweight nodes, keeping the network free and clean. Together, these innovations allow Solana to process millions of energy transactions from IoT devices and smart meters at lightning speeds and without downtime even in the most crowded network conditions.
(2) Civic Looms: Civic Looms are designed to keep all data on the network accessible and available to users. They are a part of Solana's broader architecture that aims to improve the scalability and reliability of the blockchain protocol. Civic Looms employs a variety of tactics to keep data in place, including replication and distribution of the data throughout the network. This aids in maintaining data accessibility to safeguard against situations where data is taken offline due to network congestion, node failure, or other issues.
(3) Cost-effectiveness: Solana's simplified architecture leads to lower transaction costs thus; developers and players are incentivized to use it.

The applications of AI integrated solana are decentralized automatic energy trading, where smart contracts instantly assess data from the physical world to make and execute transactions. AI can also improve fraud identification by recognizing deviations or anomalies in the blockchain data. With carbon credit tracking, AI facilitates automatic verification in real-time by processing IoT data, thus leading to verified certifications on carbon credits. Moreover, AI-driven adaptive consensus mechanisms optimize the performance of validators according to real-time network conditions, enhancing scalability and efficiency. Therefore, the combination allows high-perform, intelligent and decentralized systems.

There are several drawbacks of Solana in terms of its applicability to the energy field:

(1) Newcomer Status: Solana may face the problem of trust and competitiveness, compared to other existing platforms, as it is new in the blockchain area.
(2) Network Stability: Since its early years Solana faced intermittent downtimes, and apprehension about its viability and sustainability persisted. Nevertheless, the project's developers were willing to tackle the problem.

In addition to the usual regulatory compliance, Solana will face greater difficulties such as ensuring compliance of cross-border energy trading with international laws, and embedding renewable energy standards within its smart contracts. It can enable real-time tracking of carbon credits to comply with rules and work with regulatory entities to help create auditable blockchain standards that ensure transparency and trust. This level of customization will allow Solana to be a fully compliant and trusted player in the international energy trading system.

4.14 Cardano

Cardano is a third generation blockchain platform positioning itself as a P2P energy trading system based on scalable, secure, and sustainable technology infrastructure but not limited to it (Stamoulis, 2021). Cardano's novel feature set and PoS -based consensus mechanism make it particularly amenable for use cases relevant to the energy sector. The potential applications and benefits of Cardano in the energy sector are:

(1) Scalability: Cardano's layered architecture and consensus mechanism make Cardano process a large number of energy transactions, especially for energy trading scenarios that require real-time transactions and data processing power. The scalability of Cardano to handle high energy transactions goes far beyond standard Layer-2 techniques such as state channels and sidechains, but also takes advantage of unique Layer-2 innovations. Using its Layer-2 Hydra protocol, Cardano creates state channels which facilitate and settle off-chain transactions through on-chain security, enabling it to process microtransactions. Through the Extended UTXO (eUTXO) model, it can parallel process transactions, and throughput optimization according to the demand of the energy market. The on-chain governance of Cardano allows for adaptability to allow for upgrades necessary to cater to changing scalability. This makes Cardano uniquely powerful to handle the complex, high volume requirements of smart meters and the other IoT driven functionality of energy systems.
(2) Security and sustainability: PoS mechanism of Cardano can reduce 51% attacks, but the model is vulnerable to threats like centralization of stake pools which can lead to restrictions in network censorship, and adaptive attack vectors targeting its unique eUTXO model. In order to reduce these risks, Cardano used stake pool saturation limits, creating more incentives, and limiting the rewards for pools that became too big. Furthermore, its development process is peer-reviewed, so vulnerabilities are found and fixed before its implementation. Cardano can provide enhanced security with formal verification of smart contracts to ensure that it is resistant to bugs and exploits and advanced network monitoring tools that enable the identification of anomalies in real time to protect against fraud and breaches.
(3) Renewable Energy Tracking: Using Cardano, can set up systems to track the production, distribution, and use of renewable energy.For Cardano, the eUTXO model supports more fine-grained representation of state on chain, permitting a number of transaction data to be disclosed only if it is needed. Cardano can also leverage Mithril, an efficient and lightweight cryptographic protocol, to provide secure and private aggregated energy data, without revealing information about individual consumers. Cardano can also utilize multi-party computation (MPC), which allows for the privacy preservation of collaborative energy trading processes.
(4) Green Bonds: Energy could also issue and track green bonds on the Cardano blockchain. Green bonds are those that fund environmental projects, and funding them would, ideally, be more accountable and transparent. Cardano's compliance features are not limited with global finance regulations such as the EU Green Bond Standard or US SEC rules. A metadata feature allows detailed, auditable tracking of any issuance and use of the funds from the issuance in connection to green bonds, confirming alignment with environmental finance standards. On-chain governance of Cardano offers flexibility for smoothly implementation of regulatory updates and compliance rules between the protocol and changing legal frameworks. Cardano can also ensure the functionality of an automated reporting system via smart contracts to give regulators and stakeholders real-time documentation of compliance.
(5) Distributed Energy Resources and Smart Grid Management: The Platform can be used to collate and manage distributed energy resources, such as PV modules, and batteries to offer grid stability and optimization and facilitate grid management of DERs.

The AI-Capability to Integrate with Cardano allows applications such as, AI could dynamically set prices and match transactions between buyers and sellers. With the eUTXO model of the Platform, it can embed AI-powered predictive analytics that optimizes energy surplus/deficit and makes automatic adjustments of DERs in real-time. AI can help in automating verification of energy generation and consumption with sustainability targets which can play a role in carbon credit tracking as well. AI-driven adaptive stacking could also facilitate adaptive validator selection and network performance according to energy consumption patterns making Cardano appeal for intelligent, sustainable energy systems.

4.15 Power ledger

The Power Ledger Platform is the world's most reputable and transparent decentralized energy trading platform. It is a network built on trust, transparency, and interoperability and empowers a diverse range of energy applications using Sparkz, the energy trading token. The Power Ledger Token (POWRTR) is the powerhouse leading the Power Ledger Platform (Ahl et al., 2019). It is the driving force behind various activities and transactions within the ecosystem. The platform features privately branded trading applications, specially designed for the Power Ledger ecosystem. This unique arrangement fosters the generation of Sparkz and facilitates the exchange of POWRs. Sparkz can be obtained and redeemed with fiat currency using a closed-loop exchange facilitated by trading platforms dedicated to exchanging energy and Sparkz. These closed-loop platforms create a regulated and trusted environment for the exchange of energy and assets. Power Ledger has been implemented with several communities and energy markets across all the continents–Australia and New Zealand, Europe, and Asia.

An array of energy trading applications is included in the Power Ledger Ecosystem, where each of the applications is designed with different sets of requirements within the energy industry. The main objectives of the platform applications are to transform the Power landscape and improve efficiency and transparency during energy transactions. The different Power Ledger applications in energy sector are:

(1) P2P Trading: P2P trading allows retailers to enable P2P electricity trading between customers. Secured automated transaction processing enables them to exchange electricity and pay instantly to each other. Gain benefits that include,

choice of renewable energy sources, trade with neighbors, maximize profits from excess energy, and low settlement fees. The dual-layer blockchain system consisting of public and consortium blockchains enables the platform to process a considerable amount of transaction volume without compromising on transparency and privacy. Power Ledger utilizes microgrid energy trading models, limiting the need for large network transactions and enabling the localized scalability of the system. At the same time, real-time settlement systems automated using smart contracts enhance transaction speed and mitigate bottlenecks.

(2) NEO-Retailer: The NEO Retailer help energy retailers to manage demand and supply process payments securely and quickly. By using this application, retailers can improve their services, better manage energy distribution, and provide more value to consumers within the Power Ledger system. Based on real time energy availability, demand patterns, and real-time pricing, AI can facilitate P2P trade optimization through matching buyers and sellers. AI can implement predictive grid maintenance through smart meter data which anticipates failures or inefficiencies before they occur, allowing for seamless energy distribution. AI can also take energy arbitrage further, storing energy during off-peak periods and selling it on high-demand days for maximum profit. They even explore the use of AI for local energy planning in Power Ledger's platform as microgrids, making the energy allocation process more efficient.

(3) Microgrid/Embedded network operator (M-ENO): M-ENO is a comprehensive solution that revolutionizes energy management and trading at a localized level. By offering real-time metering, extensive data analytics, quick micro-transfers, and grid control functionalities, it enables equitable energy distribution and empowers communities to harness the benefits of DERs while aiding the development of a greener and more robust energy infrastructure. Power Ledger need not use a one-size-fits-all approach to anonymization, like that of general-purpose blockchains; instead, they can use energy-related anonymization layers (e.g., aggregating data from multiple users into community-level statistics before processing to obfuscate usage patterns). Furthermore, users can trade renewable energy credits (RECs) based on NRG tokens, while maintaining the privacy of the transaction, as its tokenized energy certificates support privacy features. In addition to that, Power Ledger can develop a real-time energy trading platform to perform on-demand data obfuscation, in which sensitive data operates under its encryption and is simply exposed for auditing (when needed).

(4) Power Purchase Agreements Dashboard: The Power Ledger Power Purchase Agreements (PPAs) Dashboard is a specialized energy data management and settlement system tailored to meet the needs of energy asset owners and operators engaged in PPAs. It provides a clear and comprehensive view of the energy sold by the energy asset owners to their buyers or the energy transactions conducted in the spot market. Power ledger's blockchain-based transparency ensures that every PPA transaction is fully auditable, aligning with international standards like RE100 and local energy certification frameworks. Power Ledger can automate compliance reporting through the use of smart contracts, limiting administrative overhead while ensuring compliance with regulations on a real-time basis. And, with modular blockchain updates the regulatory adaptation capabilities of the platform allow it to adapt to changing standards in other jurisdictions.

(5) Distributed Market Management (DMM): DMM is a powerful tool that empowers asset owners and operators to optimize their energy assets and participate effectively in the decentralized energy market. Through the use of its two-tier blockchain system, the platform secures sensitive energy data on consortium chains, minimizing the attack vector that is open to public networks. They incorporate tamper-proof IoT devices within the platform to safeguard data, thus avoiding any possibility of energy production or consumption data being manipulated. Real-time energy trading patterns monitoring with AI-powered anomaly detection, detect unauthorized transactions or corrupted data. Power Ledger uses dynamic access control mechanisms, i.e., permissions for participants change through their roles and behavior, thereby reduce insider threats. Moreover, energy-oriented cryptographic protocols preserve the authenticity of tokenized energy and carbon credits from counterfeit transactions.

(6) Electric Vehicles: Facilitating real-time metering data, data collection, user identification, and rapid transaction settlement, this application supports EVs and interfaces with the Open Charge Point Protocol (OCPP).

(7) Power Port: Automating assets related to virtual pipelines and roadside assistance, such as EVs, power port provides a mobile storage discharge facility to maintain energy supplies for primarily self-sufficient energy consumers. Power Port assists in reporting and giving up carbon credits or certificates to regulatory authorities and provides real-time metering data.

The Power Ledger Platform introduces these diverse platform applications to revolutionize energy trading and foster sustainability, efficiency, and innovation in the energy sector.

5 Summary of blockchain platforms and energy projects

The last chapter explored different types of blockchain platforms, their main uses, consensus mechanisms and disadvantages. This chapter acts as a synthesis for the information that has been covered in order to demonstrate how it can be applied practically in energy projects using these platforms. Table 1 gives a glimpse of a few popular energy projects around the world that use blockchain technology. These projects are focused around the implementation of blockchain technology in Industrial and residential sectors to facilitate various functions such as energy trading, Renewable Energy Certificate (REC) generation, demand management and more trade energy (Esther et al., 2018; Piotr, 2021).

In this study, various blockchain platforms were examined and assessed for their suitability in energy applications through an exploration of consensus mechanisms, transaction speed, and other relevant factors. Table 2 presents a summary of the different blockchain platforms considered in this study.

6 Conclusion and future scope

Blockchain is revolutionizing the energy industry by creating decentralized, transparent, and sustainable energy systems. This paper assesses various blockchain platforms in terms of their advantages, challenges, and selection, to highlight the potential blockchain platforms for energy trading applications and also include scalability, energy efficiency, regulatory compliance, cybersecurity, privacy-preserving approaches, and AI adoption. This research examines the implementation challenges and barriers including lack of interoperability with traditional energy systems, regulatory uncertainty, and resistance to adoption.

Features including improved scalability solutions, AI- optimized energy usage, and robust privacy-preserving solutions will facilitate more efficient, secure energy trading. The evolution of sustainable energy systems will also be built on the seamless integration of emerging technologies which include smart grids, Distributed Energy Resources (DERs), renewable energy certificates, *etc.* Moreover, the emergence of inter-operable blockchain ecosystems and automated energy markets based on smart contracts and IoT devices will lead to a sustainable energy market.

To encourage the use of blockchain platforms in the energy sector, this study revealed the following measures to be put into practice:

- Education and outreach: Educate people about the potential benefits of blockchain technology in the energy sector. This can be done through workshops, conferences, and other educational initiatives.
- Regulatory clarity: Local, State and Central Governments need to provide unambiguous consistent regulations for blockchain technology. This will help to reduce uncertainty and promote private investment in the energy sector.
- Partnerships: Blockchain platforms could partner with energy companies and other stakeholders to develop and implement equitable, dependable, verifiable solutions. This would help to accelerate the integration of blockchain technology in the energy industry.

Providing comprehensive analysis, this research seeks to address the need to help energy providers identify and implement appropriate blockchain platforms, enabling faster delivery of a decarbonized and more innovative energy future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AJ: Writing–original draft, Writing–review and editing. PP: Writing–review and editing. MN: Writing–review and editing.

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References

Ahl, A., Yarime, M., Tanaka, K., and Sagawa, D. (2019). Review of blockchain-based distributed energy: implications for institutional development. *Renew. Sustain. Energy Rev.* 107, 200–211. doi:10.1016/j.rser.2019.03.002

Ahmed, A. M., Olov, S., and Karl, A. (2020). "Performance evaluation of permissioned blockchain platforms," in *IEEE Asia-Pacific Conference On Computer Science And Data Engineering (CSDE)*. Australia: Gold Coast, 1–8. doi:10.1109/CSDE50874.2020.9411380

Ante, L., Steinmetz, F., and Fiedler, I. (2021). Blockchain and energy: a bibliometric analysis and review. *Renew. Sustain. Energy Rev.* 137, 110597. doi:10.1016/j.rser.2020.110597

Aparna, K., Riya, K., Rajesh, G., Smita, A., Tanwar, S., Alqahtani, F., et al. (2023). Blockchain-driven real-time incentive approach for energy management system. *Mathematics* 11 (4), 928. doi:10.3390/math11040928

Asma, K., Piyush, V., Jo, S., Beth, M., and Peter, C. (2019). Blockchain in energy efficiency: potential applications and benefits. *Energies* 12 (17), 3317. doi:10.3390/en12173317

Athira, J., Abhijith, R. M., Vyshnav, P., Susilkessav, S. B., Preetha, P. K., and Nair, M. (2023). "Peer-to-Peer energy trading using blockchain in microgrid," in *2023 5th International Conference On Energy, Power And Environment: Towards Flexible Green Energy Technologies (ICEPE)*. Shillong, India, 1–6. doi:10.1109/ICEPE57949.2023.10201643

Athira, J., Preetha, P. K., and Manjula, G. N. (2024). A secure energy trading in a smart community by integrating Blockchain and machine learning approach. *Smart Sci.* 12 (1), 105–120. doi:10.1080/23080477.2023.2270820

Athira, J. S., Preetha, P. K., and Manjula, G. N. (2022). "Smart contract-based energy trading-an overview," in *2022 IEEE 19th India Council International Conference (INDICON) India*, 1–7. doi:10.1109/INDICON56171.2022.10039697

Ayman, E., Martijin, D. V., Yashir, G.-F., Peter, P., and Epema, D. (2021a). A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. *Appl. Energy* 282, 116123. doi:10.1016/j.apenergy.2020.116123

Ayman, E., Martijn, de V., Yashar, G.-F., Peter, P., and Dick, E. (2021b). A novel decentralized platform for peer-to-peer energy trading market with blockchain technology. *Appl. Energy* 282, 116123. doi:10.1016/j.apenergy.2020.116123

Bahareh, L., and Petr, M. (2021). A comprehensive review of blockchain consensus mechanisms. *IEEE Access* 9, 43620–43652. doi:10.1109/ACCESS.2021.3065880

Bitcoin Cash (2024). "Bitcoin Cash Peer to Peer Electronic Cash". *Bitcoin Cash*. Available online at: https://bitcoincash.org/ (Accessed January 7, 2024).

Carlos, M., Felipe, O., Jamilson, D., Jean, A., Pereira, P., Maciel, R., et al. (2022). Performance and availability evaluation of the blockchain platform hyperledger fabric. *J. Supercomput.* 78, 12505–12537. doi:10.1007/s11227-022-04361-2

Chao-Qun, M., Yu-Tian, L., Yi-Shuai, R., Xun-Qi, C., Wang, Y. R., and Narayan, S. (2024). Systematic analysis of the blockchain in the energy sector: trends, issues, and future directions. *Telecommun. Policy* 48 (2), 102677. doi:10.1016/j.telpol.2023.102677

Chinmay, S., and Siddharth, S. (2018). "Blockchain platforms: a compendium," in *2018 IEEE International Conference On Innovative Research And Development (ICIRD)*. Thailand, 1–6. doi:10.1109/ICIRD.2018.8376323

Christophe, S. (2021). Proof-of-work based blockchain technology and Anthropocene: an undermined situation? *Renew. Sustain. Energy Rev.* 152, 111682. doi:10.1016/j.rser.2021.111682

DeSo (2024). "DeSo-The decentralized social blockchain" DeSo. Available online at: https://www.deso.com/ (Accessed January 20, 2024).

Devika, K. N., and Ramesh, B. (2023). Design of programmable hardware security modules for enhancing blockchain-based security framework. *Int. J. Electr. Comput. Eng.* 13 (3), 3178–3191. doi:10.11591/ijece.v13i3.pp3178-3191

Dodo, K., Low, T. J., and Manzoor, A. H. (2021). Systematic literature review of challenges in blockchain scalability. *Appl. Sci.* 11 (20), 9372. doi:10.3390/app11209372

Dong, C., Jiang, F., Li, X., Yao, A., Li, G., and Liu, X. (2021). "A blockchain-aided self-sovereign identity framework for edge-based UAV delivery system," in *2021 IEEE/ACM 21st International Symposium on Cluster, Cloud and Internet Computing (CCGrid)* (IEEE), 622–624.

Energy Web (2024). Build, connect, transform. *Energy Web*. Available online at: https://www.energyweb.org/ (Accessed February 3, 2024).

Esther, M., Johannes, G., Kerstin, R., Scott, K., Orsini, L., and Weinhardt, C. (2018). Designing microgrid energy markets: a case study: the Brooklyn Microgrid. *Appl. Energy* 210, 870–880. doi:10.1016/j.apenergy.2017.06.054

Francesco, B., Gianluca, L., Lorenzo, M., and Antonia, R. (2023). An Ethereum-based solution for energy trading in smart grids. *Digital Commun. Netw.* 9 (1), 194–202. doi:10.1016/j.dcan.2021.12.004

Hanaa, A., Maurantonio, C., and Roberto, D. P. (2022). "Analysis of polkadot: architecture, internals, and contradictions," in *2022 IEEE International Conference On Blockchain (blockchain)*, 61–70. doi:10.1109/Blockchain55522.2022.00019

Honari, K., Zhou, X., Rouhani, S., Dick, S., Liang, H., Li, Y., et al. (2022). "A scalable blockchain-based smart contract model for decentralized voltage stability using sharding technique," in *2022 IEEE International Conference On Blockchain (Blockchain)*, 124–131. doi:10.1109/blockchain55522.2022.00026

Hyeonoh, K., Eojin, Y., Jooyoung, J., Taeyoung, P., and Ahn, K. (2023). After the split: market efficiency of bitcoin Cash. *Comput. Econ.*, 1–17. doi:10.1007/s10614-023-10427-x

Hyun, J. K., Yun, S. C., Seong, J. K., Hyung, T. K., Jin, Y. G., and Yoon, Y. T. (2023). Pricing mechanisms for peer-to-peer energy trading: towards an integrated understanding of energy and network service pricing mechanisms. *Renew. Sustain. Energy Rev.* 183, 113435. doi:10.1016/j.rser.2023.113435

Jae, G. S., Eung, S. K., Hyeon, W. S., and Ju, W. J. (2021). A smart contract-based P2P energy trading system with dynamic pricing on Ethereum blockchain. *Sensors* 21 (6), 1985. doi:10.3390/s21061985

Jaysson, G., Archie, C. C., and Gregor, V. (2018). Decentralized P2P energy trading under network constraints in a low-voltage network. *IEEE Trans. Smart Grid* 10 (5), 5163–5173. doi:10.1109/TSG.2018.2878445

Jing, C., and Silvio, M. (2019). Algorand: a secure and efficient distributed ledger. *Theor. Comput. Sci.* 777, 155–183. doi:10.1016/j.tcs.2019.02.001

Kaidong, W., Ma, Y., Huang, G., and Liu, X. (2021). A first look at blockchain-based decentralized applications. *Softw. Pract. Exp.* 51 (10), 2033–2050. doi:10.1002/spe.2751

Khaoula, G. (2021). *The Volatility of Bitcoin, Bitcoin Cash, Litecoin, Dogecoin and Ethereum*. Ottawa, Canada: Diss. Université d'Ottawa/University of Ottawa. doi:10.20381/ruor-26238

Magda, F., and Manolis, V. (2021). What blockchain can do for power grids? *Blockchain Res. Appl.* 2 (1), 100008. doi:10.1016/j.bcra.2021.100008

Marc, H. (2019). Blockchain distributed ledger technology: an introduction and focus on smart contracts. *J. Corp. Account. and Finance* 31 (2), 7–12. doi:10.1002/jcaf.22421

Mirza, J. A. B., Jabbar, A., Tariq, M. I., Mohsin, J., and Jahangir, K. (2022). A low-cost, open-source peer-to-peer energy trading system for a remote community using the internet-of-things, blockchain, and Hypertext transfer protocol. *Energies* 15 (13), 4862. doi:10.3390/en15134862

Mohammad, T. Q., Mohammad, A., Fahad, A., Abdullah, A., and Goram, A. (2020). Blockchain frameworks. *Decentralised Internet Things A Blockchain Perspective*, 75–89. doi:10.1007/978-3-030-38677-1_4

Nagamani, K., Pruthu, R., and Veluri, S. T. (2021). Applications of blockchain in cryptocurrency: bitcoin and dogecoin. *Int. J. Res. Eng. Sci. Manag.* 4 (7), 87–89.

Naiyu, W., Xiao, Z., Xin, L., Zhitao, G., Wu, L., Du, X., et al. (2019). When energy trading meets blockchain in electrical power system: the state of the art. *Appl. Sci.* 9, 1561. doi:10.3390/app9081561

Nasrin, S., and Zahir, T. (2020). "On the scalability of blockchain systems," in *2020 IEEE International Conference On Cloud Engineering (IC2E)*. Australia, 124–133. doi:10.1109/IC2E48712.2020.00020

Nida, K., Tabrez, A., and Radu, S. (2019). "Feasibility of stellar as a blockchain-based micropayment system,", 11911. Springer, Cham: Lecture Notes in Computer Science, 53–65. The 2nd International Conference on Smart Blockchain. doi:10.1007/978-3-030-34083-4_6

Nitin, T., Siddharth, G., Abhishekh, G., and Prince, M. (2020). A framework for blockchain technology including features. *Emerg. Technol. Data Min. Inf. Secur. Proc. IEMIS 2020* 1, 633–645. doi:10.1007/978-981-15-9927-9_62

Padmavathi, M., and Suresh, R. M. (2019). Secure P2P intelligent network transaction using litecoin. *Mob. Netw. Appl.* 24, 318–326. doi:10.1007/s11036-018-1044-9

Pawan, K. S., Alok, K. P., and Bose, S. C. (2023). A new grey system approach to forecast closing price of Bitcoin, Bionic, Cardano, Dogecoin, Ethereum, XRP Cryptocurrencies. *Qual. and Quantity* 57 (3), 2429–2446. doi:10.1007/s11135-022-01463-0

Piotr, F. B. (2021). Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. *Energies* 14 (7), 1885. doi:10.3390/en14071885

Remya, S., and Aneena, A. (2018). A review on blockchain security. *IOP Conf. Ser. Mater. Sci. Eng.* 396 (1), 012030. doi:10.1088/1757-899X/396/1/012030

Rupali, A., Janhavi, K., and Anjali, (2023). Challenges, opportunities and risk analysis of adoption of decentralized finance applications. *ICTACT J. Soft Comput.* 14 (1). doi:10.21917/ijsc.2023.0438

Sai, S. N. B., Aryadevi, R., Balamurugan, S., Seshaiah, P., and Ramesh, M. V. (2024). Optimizing microgrid resilience: integrating IoT, blockchain, and smart contracts for power outage management. *IEEEAccess* 12, 18782–18803. doi:10.1109/ACCESS.2024.3360696

Sakineh, K., Vahid, D., and Mo, A. (2021). "Impact of blockchain technology on electric power grids--A case study in LO3 energy," in *Cryptography and Security*. doi:10.48550/arXiv.2106.05395

Sathya, A. R., and Barnali, G. B. (2020). A comprehensive study of blockchain services: future of cryptography. *Int. J. Adv. Comput. Sci. Appl.* 11 (10). doi:10.14569/IJACSA.2020.0111037

Shen, W., Ahmad, F. T., Jianhui, W., Karla, K., and Hahn, A. (2019). Energy crowdsourcing and peer-to-peer energy trading in blockchain-enabled smart grids. *IEEE Trans. Syst. Man, Cybern. Syst.* 49 (8), 1612–1623. doi:10.1109/TSMC.2019.2916565

Shuai, W., Liwei, O., Yong, Y., Xiaochun, N., Han, X., and Wang, F. Y. (2019). Blockchain-enabled smart contracts: architecture, applications, and future trends. *IEEE Trans. Syst. Man, Cybern. Syst.* 49 (11), 2266–2277. doi:10.1109/TSMC.2019.2895123

Sidharth, S. M., and Aarthi, N. (2023). "Ethereum based smart contract for peer-to-peer energy trading using blockchain technology," in *2023 IEEE International Conference On Power Electronics, Smart Grid, And Renewable Energy (PESGRE)*. India, 1–5. doi:10.1109/PESGRE58662.2023.10405209

Solana (2024). "Solana | Web3 infrastructure for everyone," in *Solana*. Available online at: https://solana.com/ (Accessed February 15, 2024).

Son, D., Al Zahr, S., and Memmi, G. (2021). "Performance analysis of an energy trading platform using the Ethereum blockchain," in *2021 IEEE International Conference On Blockchain And Cryptocurrency (ICBC)*. Sydney, Australia, 1–3. doi:10.1109/ICBC51069.2021.9461115

Stamoulis, E. (2021). "Comparative study on the environmental, political, social effects and long-term sustainability of Bitcoin, Ethereum, Tether and Cardano cryptocurrencies,". MS thesis. Ottawa, Canada: University of Twente.

Strepparava, D., Nespoli, L., Kapassa, E., Touloupou, M., Katelaris, L., and Medici, V. (2022). Deployment and analysis of a blockchain-based local energy market. *Energy Rep.* 8, 99–113. doi:10.1016/j.egyr.2021.11.283

Symiakakis, M. S., and Kanellos, F. D. (2024). ScaleNex: a scalable Blockchain-Powered electricity Market implementation for smart grid environment. *Smart Grids Sustain. Energy* 9 (2), 43. doi:10.1007/s40866-024-00230-4

Tarek, A., Jose, L. C.-V., Milos, S., Gijis, V. L., and Joao, P. S. C. (2022). Blockchain-based fully peer-to-peer energy trading strategies for residential energy systems. *IEEE Trans. Industrial Inf.* 18 (1), 231–241. doi:10.1109/TII.2021.3077008

Vahid, H., Barry, P., Brian, O., and Pierluigi, S. (2021). Practical insights to design a blockchain-based energy trading platform. *IEEE Access* 9, 154827–154844. doi:10.1109/ACCESS.2021.3127890

Valadares, D. C. G., Perkusich, A., Martins, A. F., Kamel, M. B. M., and Seline, C. (2023). Privacy-preserving blockchain technologies. *Sensors* 23 (16), 7172. doi:10.3390/s23167172

Victor, C., and Hossain, S. (2019). "Blockchain development platform comparison," in *2019 IEEE 43rd Annual Computer Software And Applications Conference (COMPSAC)*. USA, 922–923. doi:10.1109/COMPSAC.2019.00142

Vitalik, B. (2013). Ethereum white paper. *GitHub Repos.* 1, 22–23.

Wayes, T., Chau, Y., Tapan, K. S., Thomas, M., Chapman, A. C., Alam, M. J. E., et al. (2021). Peer-to-peer energy systems for connected communities: a review of recent advances and emerging challenges. *Appl. Energy* 282, 116131. doi:10.1016/j.apenergy.2020.116131

Wenyu, L., Chenglin, F., Lei, Z., Hao, X., Bin, C., and Muhammad, A. I. (2020). A scalable multi-layer PBFT consensus for blockchain. *IEEE Trans. Parallel Distributed Syst.* 32 (5), 1146–1160. doi:10.1109/TPDS.2020.3042392

Yahia, B., Gamal, A., Alkahtani, A. A., Ammar, A., Wahidah, H., and Tiong, S. K. (2021). Toward blockchain technology in the energy environment. *Sustainability* 13 (16), 9008. doi:10.3390/su13169008

Yao, A., Jiang, F., Li, X., Dong, C., Xu, J., Xu, Y., et al. (2021). "A novel security framework for edge computing based uav delivery system," in *2021 IEEE 20th International Conference On Trust, Security And Privacy In Computing And Communications (TrustCom)* (IEEE), 1031–1038.

Yao, A., Pal, S., Dong, C., Li, X., and Liu, X. (2024a). "A framework for user biometric privacy protection in UAV delivery systems with edge computing," in *2024 IEEE International Conference On Pervasive Computing And Communications Workshops And Other Affiliated Events (PerCom workshops)* (IEEE), 631–636.

Yao, A., Pal, S., Li, X., Zhang, Z., Dong, C., Jiang, F., et al. (2024b). A privacy-preserving location data collection framework for intelligent systems in edge computing. *Ad Hoc Netw.* 161, 103532. doi:10.1016/j.adhoc.2024.103532

Yonghyun, K., Ki-Hyung, K., and Jai-Hoon, K. (2020). "Power trading blockchain using hyperledger fabric," in *2020 International Conference On Information Networking (ICOIN)*. Barcelona, Spain, 821–824. doi:10.1109/ICOIN48656.2020.9016428

Yuekuan, Z., and Peter, D. L. (2023). Peer-to-peer energy sharing and trading of renewable energy in smart communities ─ trading pricing models, decision-making and agent-based collaboration. *Renew. Energy* 207, 177–193. doi:10.1016/j.renene.2023.02.125

Zeeve (2024). *A complete guide on solana blockchain and its use cases*. Solana. Available online at: https://www.zeeve.io/blog/a-complete-guide-on-solana-blockchain-and-its-use-cases/ (Accessed February 20, 2024).