



# Blockchain in energy: Overcoming barriers and harnessing opportunities for a decentralized future

AMRATANSHU <sup>1,\*</sup>, JAISWAL ADITYA <sup>2</sup> and JAISWAL ANADI <sup>1</sup>

<sup>1</sup> Student, Department of Computer Science and Engineering, Institute of Engineering and Rural Technology, Prayagraj, UP, India – 211002

<sup>2</sup> ITI Instructor, Government ITI, Soraon, Prayagraj, UP, India – 212502

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## Abstract

Blockchain technology has emerged as a promising solution for the energy sector, offering enhanced security, transparency, and innovation. With its decentralized structure and integration with smart contracts, blockchain is seen as a transformative force by various stakeholders which includes but are not limited to governments, energy companies, startups, and researchers. It enables secure and transparent transactions within a distributed network, making it a compelling alternative to traditional databases. Blockchain's potential to revolutionize energy systems is particularly evident in applications such as electric vehicle (EV) charging, decentralized energy markets, Internet of Things (IoT) integration, and peer-to-peer (P2P) energy trading.

This paper provides a review of blockchain's role in the energy industry, analyzing both the advantages and challenges inculcated in its adoption. Key benefits include secure data sharing, decentralized energy management and the creation of innovative business models. However, the technology also faces significant hurdles such as scalability, high energy consumption, and regulatory uncertainties.

Blockchain technology is poised to transform the energy sector by improving decentralization, security, and transparency. By analyzing practical initiatives and technological advancements, this research identifies strategies to overcome current obstacles and pave the way for a decentralized energy future.

**Keywords:** Blockchain; Distributed Ledger; Energy Data Security; Scalability in Blockchain; Energy Consumption in Blockchain; Blockchain Scalability; Smart Energy Grids

## 1. Introduction

Renewable energy is sourced from natural resources that naturally replenish over time, including sunlight, wind, rain, and geothermal heat [1]. The energy sector is currently undergoing a significant transformation, largely driven by the rapid uptake of renewable energy sources (RES), including wind and solar photovoltaic systems [19]. This transition has been propelled by key factors such as privatization, deregulation, and supportive governmental policies. By 2016, RES accounted for a substantial portion of the UK's electricity generation [2], contributing 24.6% of total consumption, with wind and solar power playing pivotal roles. However, the variability inherent in RES—heavily influenced by climatic conditions—presents challenges for grid stability and operational efficiency. This variability underscores the need for more flexible solutions, such as demand response mechanisms, energy storage systems, and rapid adjustments to energy supply. In addition, advancements in smart meters and digital technologies are rapidly transforming energy

\* Corresponding author: AMRATANSHU.

systems into interconnected and intelligent networks, facilitating more efficient grid management and the development of smart grid technologies [20 -21].

Renewable energy is regarded as a sustainable and environmentally beneficial alternative to conventional fossil fuels [3], offering significant potential to meet global energy demands while simultaneously reducing greenhouse gas emissions and improving air quality [4,5]. Despite its many advantages, the broader implementation of renewable energy technologies faces several challenges. One major concern is the intermittent nature of renewable energy sources, which can lead to fluctuations in supply and demand [6,7]. To address this challenge, energy storage technologies, such as batteries and pumped hydro storage, have been developed to help stabilize supply [8,9]. Additionally, the higher initial cost of renewable energy technologies compared to traditional fossil fuels remains a significant hurdle. However, this issue has been mitigated through government subsidies and incentives, along with technological innovations that have led to cost reductions over time [10].

Blockchain technology, often associated with cryptocurrencies, offers a promising solution to the complexities of decentralized energy systems. As a distributed ledger, blockchain facilitates the secure and transparent recording of transactions without the need for a central authority. By utilizing consensus algorithms, blockchain ensures data integrity and security across a decentralized network. The addition of smart contracts—automated, self-executing agreements—further enhances blockchain's potential, enabling peer-to-peer (P2P) energy trading [11, 22], the development of decentralized energy markets, and stronger integration with the Internet of Things (IoT).

The use of blockchain in energy systems is gaining momentum, with various startups, research initiatives, and utility companies exploring its capacity to support low-carbon transitions and optimize system efficiency [12]. Nevertheless, challenges related to scalability, cost, and regulatory frameworks need to be overcome to enable broader adoption of blockchain in the energy sector. This paper seeks to provide a comprehensive analysis of blockchain technology's potential in energy systems, exploring its foundational principles, key applications such as P2P energy trading, and ongoing research and pilot programs. It will also address the challenges hindering effective integration of blockchain within energy infrastructures and offer insights into the future trajectory of decentralized energy systems.

Our research aims to bridge the existing knowledge gap by delivering a timely and thorough review. The specific contributions of this study are outlined as follows:

We provide an overview of the core principles of distributed ledger technologies (DLT) [13], focusing on the various system architectures and consensus mechanisms that underpin the technical foundation of blockchain systems. A significant amount of blockchain knowledge is derived not only from traditional academic sources such as journals and conference proceedings but also from alternative sources like forums, blogs, wikis, white papers, and industry reports. The introductory section of this paper consolidates key information from these diverse sources, offering readers a holistic understanding of the broader DLT landscape before delving into energy-specific applications. We thoroughly examine the advantages and limitations of each technology type and its relevance for various use cases.

Cryptocurrency-related blockchain technology has shown to be a strong option for decentralizing energy infrastructure. Blockchain technology uses smart contracts and distributed ledger technology (DLT) to provide safe, unchangeable transactions and effective integration of renewable energy sources. Opportunities for innovation in energy systems are presented by its applications, which range from decentralized grid management to peer-to-peer energy trading. In addition to offering answers for scalability and legal barriers, this article examines how blockchain might help with issues including grid unpredictability, data integrity, and market inefficiencies.

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## 2. Materials and methods

This section outlines the methodologies and processes employed to explore the incorporation of blockchain technology [14] within the energy sector. The primary aim of this research was to pinpoint significant blockchain use cases in the energy domain, evaluate their advantages and obstacles, and examine the latest advancements in the applications of blockchain technology. Below, we elaborate on the systematic review approach, and the analytical techniques utilized.

### 2.1. Literature Review

The groundwork for this investigation is established through an extensive literature review. The process commenced with the identification of pertinent literature published from 2015 to 2024, specifically targeting studies that examine blockchain applications in energy systems. This encompassed peer-reviewed journal articles, industry reports, white papers, and grey literature from credible sources. Our search primarily utilized academic databases such as IEEE Xplore,

Google Scholar, ScienceDirect, and Scopus, employing specific search terms like "blockchain in energy," "peer-to-peer energy trading" [15], "decentralized energy systems using blockchain," and "blockchain for energy storage." In addition to academic sources, we also explored industry publications, consultancy reports, and white papers that offered insights into practical applications and pilot initiatives.

The rapid adoption of renewable energy sources (RES), such as solar and wind, has significantly transformed global energy systems. However, the intermittent nature of these energy sources presents challenges related to grid stability, demand-supply fluctuations, and operational efficiency [5]. To address these challenges, advanced technologies, including blockchain, have gained attention as a potential solution. Blockchain, as a form of distributed ledger technology (DLT), ensures secure, transparent, and tamper-proof transaction records across decentralized networks [15].

A notable application of blockchain in the energy sector is **peer-to-peer (P2P) energy trading**, where producers and consumers can directly exchange surplus energy without intermediaries. Projects like Power Ledger and LO3 Energy have successfully implemented blockchain-based P2P trading platforms, demonstrating reduced transaction costs, improved transparency, and enhanced participation of smaller producers in the energy market [17]. Similarly, tokenized energy systems, such as SolarCoin, provide economic incentives to renewable energy producers, thereby promoting clean energy generation [7].

Blockchain also facilitates **decentralized energy management**, enabling the integration of distributed energy resources (DERs) into existing grids. By leveraging smart contracts, blockchain automates processes such as demand-response management, renewable energy certification, and energy supply chain transparency [10]. These capabilities are critical for developing **smart grids**, which rely on real-time data exchange to optimize energy distribution and enhance operational efficiency [2].

Despite its potential, blockchain adoption in the energy sector faces significant challenges. Scalability remains a pressing concern, as traditional consensus mechanisms, such as Proof of Work (PoW), are resource-intensive and inefficient for large-scale applications. Energy-efficient alternatives, including Proof of Stake (PoS) and Delegated Proof of Stake (DPoS), have been proposed to address these limitations [18]. Regulatory uncertainties and integration with legacy systems further hinder the widespread deployment of blockchain technology in energy systems [14].

Recent advancements, such as **Layer 2 scaling solutions**, have shown promise in enhancing blockchain's scalability and transaction throughput. Technologies like rollups and sidechains enable off-chain processing, reducing the computational burden on the main blockchain [18]. Additionally, hybrid blockchain models that combine public and private networks offer a balanced approach to maintaining transparency while ensuring privacy and security in energy transactions [17].

Several studies emphasize the importance of integrating blockchain with other emerging technologies, such as **artificial intelligence (AI)** and the **Internet of Things (IoT)**. AI-driven predictive analytics can improve energy demand forecasting and decision-making, while IoT devices enable real-time grid monitoring and dynamic energy management [4]. These synergies can further enhance the efficiency and sustainability of decentralized energy systems.

This review highlights blockchain's potential to revolutionize the energy sector by addressing inefficiencies, enhancing transparency, and enabling decentralized operations. While ongoing research and pilot projects demonstrate significant progress, future efforts must focus on overcoming scalability challenges, establishing regulatory frameworks, and fostering cross-disciplinary collaboration to unlock blockchain's full potential in energy systems.

## 2.2. Distributed Ledger Technology (DLT)

Distributed Ledger Technology (DLT) [13] is defined as a framework that facilitates the storage of information across various locations, ensuring that records are maintained in a secure and transparent manner by a decentralized network instead of a single governing body. In this system, each participant, referred to as a node, possesses a copy of the distributed ledger, and any modifications or updates made to the ledger are simultaneously propagated to all copies. This mechanism guarantees the integrity, transparency, and security of the data.

A fundamental aspect of DLT is its implementation of consensus mechanisms, which serve to validate transactions and ensure that all nodes in the network agree on the current state of the ledger. Among the widely utilized consensus algorithms in DLT are Proof of Work (PoW), Proof of Stake (PoS), and Practical Byzantine Fault Tolerance (PBFT). Each

of these algorithms outlines the process by which nodes achieve consensus regarding the validity of transactions that can be incorporated into the ledger.

Blockchain technology is one of the most prominent applications of DLT, where data is organized into interconnected "blocks" and secured using cryptographic techniques. Although blockchain is the most recognized variant of DLT, other forms such as Directed Acyclic Graphs (DAGs) are also employed in certain alternative ledger systems.

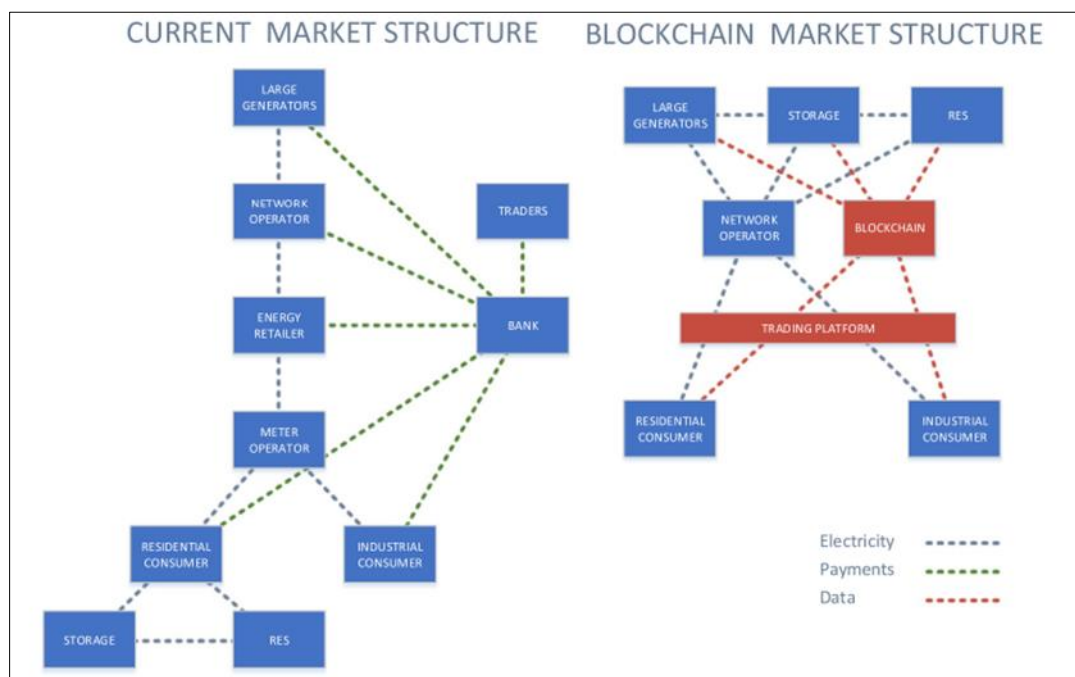
DLT presents numerous advantages, including heightened security through cryptographic measures, increased transparency as all participants can access the ledger, and diminished dependence on intermediaries for conducting transactions. It is especially advantageous for scenarios that demand transparent, secure, and tamper-proof data management, such as in supply chain management, financial transactions, and decentralized applications (dApps).

### 2.3. Systematic Review of Blockchain Use Cases in the Energy Sector

Following the collection of relevant literature, we performed a systematic review to categorize blockchain use cases in the energy sector. The objective was to pinpoint critical areas where blockchain could potentially transform or enhance existing practices. The identified blockchain use cases include:

**Renewable Energy Integration:** A significant application of blockchain in the energy sector involves its role in integrating renewable energy sources (such as solar and wind) into current power grids. Blockchain-enabled systems support real-time energy trading, decentralize energy production, and enhance the management of distributed energy resources (DERs). Platforms like Energy Web Token and Power Ledger facilitate tokenized energy trading, enabling consumers and prosumers (those who both consume and produce energy) to interact directly without relying on a centralized intermediary.

**Energy Trading and Peer-to-Peer (P2P) Marketplaces:** Blockchain has facilitated the establishment of decentralized, peer-to-peer energy trading platforms. For instance, Power Ledger has implemented P2P trading in various countries, where energy is traded locally over blockchain networks, allowing consumers to buy and sell surplus energy directly. This approach reduces transaction costs and lessens reliance on centralized utility providers, while also promoting transparent pricing and enhancing liquidity for smaller energy producers.



**Figure 1** Transformation of market with blockchains according to PWC [18]

**Smart Grid Management:** Blockchain is pivotal in managing decentralized energy grids, enabling efficient load balancing and real-time monitoring of energy demand and supply across distributed networks. It ensures secure and automated data exchanges between energy producers, consumers, and grid operators. A notable example is LO3 Energy, where blockchain technology underpins the management of microgrids and localized energy markets in Brooklyn, New York.

**Energy Supply Chain Transparency:** Blockchain significantly improves the traceability of energy from its origin to its consumption point. Smart contracts and decentralized ledger systems are employed to verify energy production claims, track the source of energy (such as confirming renewable energy certificates), and mitigate fraudulent activities. An illustrative case is SolarCoin, a digital currency awarded to solar energy producers, which provides proof of clean energy generation through blockchain verification.

Each use case was assessed for its technical specifications, the blockchain platforms utilized (such as Ethereum and Hyperledger), consensus algorithms (including Proof of Work and Proof of Stake), transaction types (like energy certificates and tokenized energy transactions), and the maturity of implementation (ranging from proof-of-concept to operational systems).

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### 3. Assessment of Blockchain Benefits and Drawbacks

For each blockchain application, we analyzed its potential advantages and challenges.

#### 3.1. Benefits [17]

- **Transparency:** The decentralized nature of blockchain guarantees that energy transactions are transparent, auditable, and immutable, which is crucial for energy trading and the certification of renewable energy credits, where trust and authenticity are paramount.
- **Security:** The cryptographic features of blockchain enhance security against fraud and cyberattacks, safeguarding sensitive energy data and transactions in an increasingly digital energy landscape. Example: Power Ledger's P2P energy trading in Australia.
- **Cost Efficiency:** By eliminating intermediaries and automating transactions through smart contracts, blockchain reduces the costs associated with energy trading, grid management, and administrative tasks. Power Ledger has reported significant operational cost savings due to the removal of middlemen.
- **Decentralization:** Blockchain fosters decentralized energy systems, empowering local communities to take control of their energy production, consumption, and distribution, thereby promoting energy independence and reducing reliance on large centralized utilities.

#### 3.2. Challenges [17]

- **Scalability:** The scalability of blockchain systems in energy markets presents a notable challenge. High transaction volumes and the energy-intensive nature of certain consensus mechanisms (like Proof of Work) may hinder the efficiency of blockchain applications in expansive energy grids.
- **Regulatory Uncertainty:** The lack of clear and unified regulations for blockchain applications in the energy sector poses a significant obstacle. In various regions, regulatory bodies are still attempting to determine how to incorporate blockchain into existing legal frameworks and energy regulations.
- **Integration with Legacy Systems:** The implementation of blockchain technology in the energy sector necessitates compatibility with current infrastructure. Many energy systems are built on traditional, centralized technologies, making the transition to decentralized blockchain systems potentially costly and complex.

#### 3.3. Solution to the challenges

To address the challenges associated with the adoption of blockchain technology in the energy sector, various solutions can be employed to improve the viability, scalability, and efficiency of blockchain applications. The following outlines key strategies aimed at overcoming the identified obstacles:

##### 3.3.1. Scalability Challenges

**Implementation of Energy-Efficient Consensus Mechanisms:** A primary constraint of blockchain technology, particularly in large-scale applications within the energy sector, is the scalability of blockchain networks. Conventional consensus mechanisms, such as Proof of Work (PoW), tend to be resource-heavy and slow. To alleviate this issue, it is advisable to adopt energy-efficient consensus alternatives like Proof of Stake (PoS), Proof of Authority (PoA), and Delegated Proof of Stake (DPoS). These mechanisms are less energy-intensive, demand fewer computational resources, and can support a greater transaction throughput, which is essential for applications involving energy trading, grid management, and real-time data sharing.

### 3.3.2. Layer 2 Scaling Solutions

To further enhance scalability, Layer 2 solutions [18]—including state channels, sidechains, and rollups—can be utilized. These approaches facilitate off-chain transactions, thereby reducing the burden on the main blockchain and enabling quicker, more efficient processing of substantial data and transaction volumes. This is particularly advantageous for applications necessitating real-time energy transactions, such as peer-to-peer energy trading.

### 3.3.3. Regulatory and Legal Challenges

**Creation of Comprehensive Regulatory Frameworks:** A significant barrier to the widespread implementation of blockchain in the energy sector is the lack of clear and cohesive regulatory frameworks. It is essential for governments and regulatory authorities to collaborate with blockchain developers, energy providers, and industry stakeholders to formulate regulations that govern blockchain-based energy transactions. This includes addressing critical issues such as the legal recognition of smart contracts, the classification of blockchain tokens or energy credits, and ensuring adherence to existing energy trading regulations. Well-defined regulations will promote trust in blockchain systems and stimulate their adoption.

### 3.3.4. Collaboration Between Public and Private Sectors

A cooperative approach involving both public and private sectors can facilitate the establishment of these regulatory frameworks. By creating industry coalitions or partnering with blockchain-focused organizations, governments can develop standards and regulations that ensure security, equity, and transparency within blockchain-driven energy systems. This collaboration will also help mitigate concerns regarding data privacy, consumer protection, and market stability.

### 3.3.5. Interoperability

**Standardization of Protocols and Data Formats:** Achieving interoperability among various blockchain networks and the current energy infrastructure is vital for the successful integration of blockchain into the energy sector. The absence of standardization across blockchain platforms and energy systems has resulted in isolated silos, hindering seamless interaction among stakeholders. To address this, efforts should focus on establishing global standards for blockchain protocols, smart contract languages, and data formats. Such standardization would enable diverse blockchain systems to communicate effectively and ensure smooth integration with traditional energy management systems.

**Hybrid Blockchain Models:** Employing a hybrid blockchain model, which integrates elements of both public and private blockchains, can also effectively tackle interoperability challenges. This approach allows for the maintenance of privacy and security in energy transactions through private blockchains, while utilizing public blockchains for transparency and open access in areas such as renewable energy certification and supply chain tracking. This model enables energy companies to harness the advantages of both blockchain types while ensuring compatibility with existing systems.

### 3.3.6. Transparency in Energy Supply Chains

**Utilization of Smart Contracts for Real-Time Monitoring and Automation:** Ensuring transparency in energy supply chains is essential for verifying and tracing energy sources, certifications, and transactions. Smart contracts can automate functions such as tracking renewable energy origins, certifying energy production, and ensuring compliance with environmental regulations. By documenting all transactions and agreements on an immutable ledger, blockchain offers a transparent and auditable record of energy production and consumption. This transparency would bolster consumer trust and diminish inefficiencies caused by intermediaries.

**Collaboration with Supply Chain Partners:** The effectiveness of blockchain in enhancing transparency is maximized when it is integrated throughout the entire energy supply chain. Energy producers, distributors, regulators, and consumers must work together to implement blockchain technology across their operations. This collaboration ensures that every phase of the energy supply chain is documented and accessible to relevant stakeholders. By providing a unified source of truth, blockchain can minimize energy waste, eliminate fraud, and streamline the reconciliation process between energy producers and consumers.

## 3.4. Review of Blockchain Developments by Commercial Startups and Research Organizations

In addition to academic research, we assessed advancements made by commercial startups and research institutions, reviewing ongoing blockchain initiatives in energy sectors globally. These initiatives were categorized by:

- **Blockchain Type:** Whether the system is based on a public, private, or hybrid blockchain architecture.

- **Consensus Mechanism:** The type of consensus mechanism employed in the system, such as Proof of Work (PoW), Proof of Stake (PoS), or Proof of Authority (PoA).
- **Energy Sub-Sector Focus:** The specific energy sub-sector targeted by the blockchain initiative (e.g., renewable energy, energy trading, grid management).
- **Stage of Implementation:** The current phase of the project, whether it is in proof-of-concept, pilot, or full-scale implementation.

For example, Power Ledger and Energy Web Foundation are prominent commercial entities that have developed blockchain solutions for renewable energy trading and decentralized grid management. LO3 Energy has showcased blockchain's potential for community-driven, localized energy systems, while WePower has introduced tokenized energy contracts enabling users to purchase energy in advance.

### 3.5. Statistical Analysis

To quantify the findings, we conducted basic statistical analyses on the collected data. Descriptive statistics, including frequency distributions, were utilized to highlight prevalent blockchain use cases across various energy sub-sectors. Cross-tabulation analysis was employed to identify correlations between the type of blockchain technology (e.g., public vs. private) and the focus of the energy sub-sector (e.g., renewable integration vs. trading systems).

### 3.6. Limitations of the Study

Despite the extensive data collection, several limitations were acknowledged:

- **Limited Access to Proprietary Data:** Some commercial blockchain projects, especially those still in early pilot stages or proprietary in nature, were excluded from the study.
- **Rapid Technological Advancements:** Given the swift evolution of blockchain technology, some recently implemented applications may not have been captured due to delays in publication.

This methodological framework provided a solid basis for understanding the practical applications, challenges, and advantages of integrating blockchain technology into the energy sector, this research adopts a systematic framework to investigate the opportunities and obstacles associated with blockchain technology in the energy sector, particularly its potential to facilitate decentralized energy systems. The research methodology comprises three primary elements: a thorough literature review, case study evaluations, and a qualitative synthesis of the results.

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## 4. Conclusion

Blockchain technology is poised to revolutionize the energy sector by addressing inefficiencies, enhancing transparency, and enabling decentralized systems. While challenges such as scalability, interoperability, and regulatory uncertainties persist, advancements in Layer 2 scaling solutions and global policy frameworks offer promising solutions. The convergence of blockchain with artificial intelligence (AI) for predictive energy analytics and the Internet of Things (IoT) for real-time grid monitoring presents transformative opportunities for dynamic and efficient energy management. Collaborative efforts among governments, researchers, and industry stakeholders will be pivotal in overcoming existing barriers and unlocking blockchain's full potential, driving the transition toward a secure, efficient, and sustainable energy future.

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## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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## References

- [1] Shahzad, U. (2017). The Need for Renewable Energy Sources. *Information Technology & Electrical Engineering*, 6(1), 16–18.
- [2] Liu, J., Wang, J., & Cardinal, J. (2022). Evolution and Reform of UK Electricity Market. *Renewable and Sustainable Energy Reviews*, 161, 112317.

- [3] Solarin, S. A., Bello, M. O., & Bekun, F. V. (2021). Sustainable Electricity Generation: The Possibility of Substituting Fossil Fuels for Hydropower and Solar Energy in Italy. *International Journal of Sustainable Development & World Ecology*, 28(5), 429–439.
- [4] Shahsavari, A., & Akbari, M. (2018). Potential of Solar Energy in Developing Countries for Reducing Energy-Related Emissions. *Renewable and Sustainable Energy Reviews*, 90, 275–291.
- [5] Omer, A. M. (2008). Energy, Environment and Sustainable Development. *Renewable and Sustainable Energy Reviews*, 12(9), 2265–2300.
- [6] Sovacool, B. K. (2009). The Intermittency of Wind, Solar, and Renewable Electricity Generators: Technical Barrier or Rhetorical Excuse? *Utilities Policy*, 17(3–4), 288–296.
- [7] Sinsel, S. R., Riemke, R. L., & Hoffmann, V. H. (2020). Challenges and Solution Technologies for the Integration of Variable Renewable Energy Sources—A Review. *Renewable Energy*, 145, 2271–2285.
- [8] Ma, T., Yang, H., & Lu, L. (2014). Feasibility Study and Economic Analysis of Pumped Hydro Storage and Battery Storage for a Renewable Energy Powered Island. *Energy Conversion and Management*, 79, 387–397.
- [9] Guezgouz, M., Jurasz, J., Bekkouche, B., Ma, T., Javed, M. S., & Kies, A. (2019). Optimal Hybrid Pumped Hydro-Battery Storage Scheme for Off-Grid Renewable Energy Systems. *Energy Conversion and Management*, 199, 112046.
- [10] Abdmouleh, Z., Alammari, R. A., & Gastli, A. (2015). Review of Policies Encouraging Renewable Energy Integration & Best Practices. *Renewable and Sustainable Energy Reviews*, 45, 249–262.
- [11] Swan, M. (2015). *Blockchain: Blueprint for a New Economy*. O'Reilly Media Inc.
- [12] Office of Gas and Electricity Markets (Ofgem). (2017). Consumer Empowerment and Protection. Retrieved from <https://www.ofgem.gov.uk/publications/consumer-empowerment-and-protection>
- [13] Gorbunova, M., Masek, P., Komarov, M., & Ometov, A. (2021). Distributed Ledger Technology: State-of-the-Art and Current Challenges. *IEEE Access*, 9, 116713–116725.
- [14] Rejeb, A., Rejeb, K., Zrelli, I., Süle, E., & Iranmanesh, M. (2024). Blockchain Technology in the Renewable Energy Sector: A Comprehensive Review. *Renewable and Sustainable Energy Reviews*, 150, 111509.
- [15] Soto, E. A., Bosman, L. B., Wollega, E., & Leon-Salas, W. D. (2024). Peer-to-Peer Energy Trading: A Review of Enabling Technologies. *Renewable and Sustainable Energy Reviews*, 150, 111523.
- [16] Gawusu, S., Tando, M. S., Ahmed, A., Jamatutu, S. A., Mensah, R. A., Das, O., Mohammed, A.-L., Yakubu, I. N., & Ackah, I. (2024). Decentralized Energy Systems and Blockchain Technology: Implications for Alleviating Energy Poverty. *Renewable and Sustainable Energy Reviews*, 150, 111512.
- [17] Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., McCallum, P., & Peacock, A. (2019). Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities. *Renewable and Sustainable Energy Reviews*, 100, 143–174.
- [18] Mandal, M., Chishti, M. S., & Banerjee, A. (2023). Investigating Layer-2 Scalability Solutions for Blockchain Applications. *IEEE Access*, 11, 12345–12356.
- [19] Techfloyd. Why and how blockchain is reshaping the energy sector. Techfloyd. Retrieved January 24, 2025, from <https://www.techfloyd.com/why-how-blockchain-is-reshaping-the-energy-sector/>
- [20] Anglen, J. (n.d.). Exploring blockchain's impact on energy & sustainability. Rapid Innovation. Retrieved January 25, 2025, from <https://www.rapidinnovation.io/post/blockchain-and-sustainable-energy-eco-friendly-solutions-2024>
- [21] Ganjineh, H. (2023, July 18). The blockchain disruption: Transforming the energy industry with transparency, efficiency, and decentralization. *Forbes*. Retrieved January 25, 2025, from <https://www.forbes.com/councils/forbestechcouncil/2023/07/18/the-blockchain-disruption-transforming-the-energy-industry-with-transparency-efficiency-and-decentralization/>
- [22] Finance Magnates. (2023, May 25). The use of blockchain technology in the energy industry to promote sustainability. Finance Magnates. Retrieved January 25, 2025, from <https://www.financemagnates.com/cryptocurrency/education-centre/the-use-of-blockchain-technology-in-the-energy-industry-to-promote-sustainability/>