International Journal of Science and Technology Research Archive

ISSN: 0799-6632 (Online)

Journal homepage: https://sciresjournals.com/ijstra/

(REVIEW ARTICLE)

Check for updates

Blockchain for transparent and secure supply chain management in renewable energy

Ekene Cynthia Onukwulu [1, *], Ikiomoworio Nicholas Dienagha [2], Wags Numoipiri Digitemie [3] and Peter Ifechukwude Egbumokei [4]

[1] *Independent Researcher, Nigeria.*
[2] *Shell Petroleum Development Company, Lagos Nigeria.*
[3] *Shell Energy Nigeria PLC.*
[4] *Shell Nigeria Gas (SEN/ SNG), Nigeria.*

International Journal of Science and Technology Research Archive, 2022, 03(01), 251-272

Publication history: Received on 18 August 2022; revised on 26 September 2022; accepted on 29 September 2022

Article DOI: https://doi.org/10.53771/ijstra.2022.3.1.0103

Abstract

Blockchain technology has emerged as a transformative tool for enhancing transparency, traceability, and security within supply chain management, particularly in the renewable energy sector. With increasing global demand for renewable energy sources, the complexity of managing decentralized supply chains has grown, necessitating more robust systems for tracking resources, transactions, and ensuring compliance. Blockchain offers a decentralized, immutable ledger that ensures all transactions are recorded transparently and cannot be altered, providing a foundation for greater accountability and trust among stakeholders. In renewable energy supply chains, blockchain can effectively address several critical challenges, including the verification of the origin of materials, such as solar panels, wind turbines, and batteries. This ensures that the sourcing of raw materials is done ethically, sustainably, and in line with environmental and social governance standards. Furthermore, blockchain facilitates real-time tracking of products from manufacturing to deployment, offering enhanced visibility and reducing the risk of fraud, theft, or errors. The integration of blockchain with Internet of Things (IoT) devices can further optimize the renewable energy supply chain by enabling automatic data recording and monitoring of the performance and condition of energy assets. This leads to improved asset management and predictive maintenance, thus reducing operational costs and increasing efficiency. Additionally, smart contracts powered by blockchain can automate and streamline transactions, reducing paperwork and delays, and ensuring compliance with contractual obligations. Overall, the application of blockchain in renewable energy supply chains holds significant promise in driving sustainability, reducing inefficiencies, and fostering collaboration between various stakeholders, including manufacturers, suppliers, and end-users. By leveraging blockchain's capabilities, the renewable energy sector can build more transparent, secure, and efficient supply chains, contributing to a more sustainable energy future.

Keywords: Blockchain; Renewable Energy; Supply Chain Management; Transparency; Security; Traceability; Smart Contracts; Sustainability; Iot; Compliance

1. Introduction

The renewable energy sector has seen rapid growth as the global demand for cleaner, sustainable energy sources increases. However, this growth has also brought forth significant challenges in managing the complex supply chains involved in the production, distribution, and storage of renewable energy. From sourcing raw materials for solar panels and wind turbines to the final delivery of energy, the supply chain involves numerous stakeholders, each with their own set of processes, systems, and data (Adejugbe & Adejugbe, 2014, Bassey, 2022, Okeke, et al., 2022, Dickson & Fanelli,

* Corresponding author: Ekene Cynthia Onukwulu

2018). This complexity often leads to inefficiencies, delays, and issues with accountability, which can undermine the sustainability efforts of the renewable energy industry.

One of the key issues facing renewable energy supply chains is the lack of transparency and traceability. The journey of a product or component—from the extraction of raw materials to its installation in renewable energy systems—can be difficult to track, making it hard to verify sustainability claims and ensure compliance with environmental standards. Additionally, ensuring the security of transactions and data within the supply chain is critical, as the involvement of multiple parties increases the risk of fraud, counterfeiting, and cyber threats (Agupugo, et al., 2022, da Silva Veras, et al., 2017, Dominy, et al., 2018, Napp, et al., 2014).

To address these challenges, blockchain technology has emerged as a promising solution. Blockchain, a decentralized and immutable digital ledger, provides a secure, transparent, and tamper-proof system for tracking the movement of goods and verifying transactions. By enabling real-time tracking and recording of every transaction within the supply chain, blockchain ensures that all participants have access to the same reliable data (Adeniran, et al., 2022, Okeke, et al., 2022, Dong, et al., 2019, Lindi, 2017). This transparency not only improves accountability but also enhances trust among stakeholders, from raw material suppliers to end consumers. With its ability to secure data and facilitate direct peer-to-peer transactions, blockchain technology offers a powerful tool to overcome the current limitations in renewable energy supply chains, promoting greater efficiency, sustainability, and security in the industry.

2. Blockchain Technology: Key Concepts and Benefits

Blockchain technology is revolutionizing numerous industries by providing a secure, transparent, and decentralized platform for transactions and data management. At its core, blockchain operates as a distributed ledger system, where data is stored in "blocks" linked together in chronological order, forming a chain. This structure ensures that once information is recorded, it cannot be altered or tampered with without being immediately detectable, providing a high level of data integrity and security. In essence, blockchain eliminates the need for intermediaries or central authorities, as all participants in the network have access to the same data in real-time, ensuring transparency and reducing the potential for fraud or errors.

One of the fundamental characteristics of blockchain technology is its decentralization. Unlike traditional centralized systems where data is stored and controlled by a single entity, blockchain operates on a peer-to-peer network of nodes. Each participant, or "node," has a copy of the entire blockchain, ensuring that no single entity can control or manipulate the data. This decentralized nature enhances the security of the system, as it is much harder for malicious actors to alter or corrupt data when it is distributed across numerous participants (Okoroafor, et al., 2022, Okwiri, 2017, Olayiwola & Sanuade, 2021, Shahbaz, et al., 2017). This is particularly valuable in industries where trust, accountability, and data integrity are essential, such as in supply chain management.

Immutability is another key feature of blockchain technology. Once a transaction is recorded on the blockchain, it cannot be modified or deleted. This ensures that the data is permanent and tamper-proof, which is critical for maintaining an accurate and trustworthy record of events. Immutability also provides a transparent audit trail, allowing all participants in the supply chain to trace the history of a product or component at any given point in time. This feature is particularly important in industries where provenance and certification of goods are necessary for regulatory compliance or sustainability purposes.

Transparency is the third defining characteristic of blockchain technology. In a blockchain network, every transaction is recorded on the public ledger, and all participants have access to the same information. This creates an environment where every stakeholder in the supply chain—whether a manufacturer, supplier, distributor, or consumer—can verify the authenticity and status of a product in real-time (Akpan, 2019, Bassey, 2022, Oyeniran, et al., 2022, Dufour, 2018, Martin, 2022). This level of transparency is particularly valuable in industries like renewable energy, where sustainability claims and ethical sourcing practices are critical, and verifying the origin and journey of materials can be complex and difficult to track using traditional methods.

In the context of supply chain management, blockchain technology offers several features that enhance security, traceability, and data integrity. The security provided by blockchain comes from its use of cryptographic techniques to secure data, making it nearly impossible for unauthorized actors to access or manipulate information. Each transaction is verified by multiple participants in the network before being added to the blockchain, which reduces the likelihood of fraud or errors (Aftab, et al., 2017, Okeke, et al., 2022, El Bilali, et al., 2022, McCollum, et al., 2018). This is particularly relevant in industries like renewable energy, where supply chains often involve numerous actors across different

regions, each with varying degrees of trustworthiness. By using blockchain, companies can ensure that all transactions are legitimate and secure, from the sourcing of raw materials to the delivery of the final product.

Traceability is another critical feature of blockchain technology that is highly relevant to supply chain management. In a traditional supply chain, it can be challenging to trace the origin of a product or component, particularly if it passes through multiple stages of production and distribution. Blockchain solves this problem by providing an immutable record of every step in the supply chain (Kabeyi & Olanrewaju, 2022, Kinik, Gumus & Osayande, 2015, Lohne, et al., 2016). Each time a product is transferred or processed, a new transaction is recorded on the blockchain, creating a transparent and verifiable history. This traceability is particularly important in renewable energy, where the materials used to create energy systems—such as solar panels, wind turbines, and batteries—must meet specific environmental and ethical standards. Blockchain enables companies to track the origin of raw materials, verify the sustainability of production processes, and ensure compliance with regulatory requirements.

Data integrity is another benefit of blockchain technology that is essential in supply chain management. In traditional systems, data can be altered or corrupted due to human error, fraud, or system malfunctions. With blockchain, every transaction is recorded in a way that ensures its accuracy and integrity. Since each block is linked to the previous one, any attempt to alter the data would require changing every subsequent block in the chain, which is virtually impossible without being detected (Sule, et al., 2019, Vesselinov, et al., 2021, Wennersten, Sun & Li, 2015, Zhang & Huisingh, 2017). This ensures that the information stored on the blockchain is accurate, reliable, and trustworthy, making it an invaluable tool for companies looking to optimize their supply chain processes.

The benefits of blockchain for supply chain management are particularly pronounced in the renewable energy sector. Renewable energy supply chains are complex and involve multiple stakeholders, including raw material suppliers, manufacturers, distributors, and end customers. Each step in the process can introduce inefficiencies, errors, or fraud, especially when dealing with large quantities of materials and products across vast distances (Adejugbe, 2020, Beiranvand & Rajaee, 2022, Okeke, et al., 2022, Oyeniran, et al., 2022). By integrating blockchain technology, companies in the renewable energy sector can streamline their operations, reduce costs, and enhance the transparency and security of their supply chains.

One of the key benefits of blockchain for renewable energy supply chains is improved sustainability. As the demand for renewable energy continues to grow, the industry faces increasing pressure to ensure that the materials used to generate energy are sourced ethically and sustainably. Blockchain provides a way to verify the origin and journey of raw materials, ensuring that they are sourced responsibly and in compliance with environmental and social standards (Adenugba & Dagunduro, 2021, Popo-Olaniyan, et al., 2022, Eldardiry & Habib, 2018, Zhao, et al., 2022). For example, companies can use blockchain to verify that the metals used in solar panels or wind turbines are sourced from mines that adhere to environmental regulations and fair labor practices. This level of transparency is critical for companies looking to build trust with consumers, regulators, and investors who are increasingly focused on sustainability and ethical sourcing.

Another significant benefit of blockchain for renewable energy supply chains is the ability to enhance efficiency and reduce costs. By providing real-time access to data and automating key processes, blockchain can help companies optimize their supply chain operations. For example, smart contracts—self-executing contracts with the terms of the agreement directly written into code—can be used to automate payments and other transactions, reducing the need for intermediaries and minimizing delays (Olufemi, Ozowe & Komolafe, 2011, Ozowe, 2018, Pan, et al., 2019, Shahbazi & Nasab, 2016). This can significantly reduce administrative costs and improve the overall efficiency of the supply chain. Additionally, blockchain's transparency and traceability features can help identify inefficiencies or bottlenecks in the supply chain, allowing companies to address these issues proactively.

Blockchain also improves accountability within renewable energy supply chains. Since all transactions are recorded on an immutable ledger, companies can be held accountable for their actions and decisions at every stage of the supply chain (Adejugbe & Adejugbe, 2018, Bello, et al., 2022, Okeke, et al., 2022, Popo-Olaniyan, et al., 2022). This is particularly important in industries where compliance with regulatory standards is essential. Blockchain allows companies to prove that they have met all necessary requirements, such as those related to environmental impact, labor practices, and product quality, reducing the risk of regulatory fines or reputational damage.

In conclusion, blockchain technology offers a transformative solution for optimizing supply chain management in the renewable energy sector. By providing enhanced security, traceability, and transparency, blockchain helps companies ensure the integrity of their supply chains, improve operational efficiency, and meet sustainability and compliance

standards. As the renewable energy sector continues to grow and evolve, blockchain will play an increasingly important role in shaping the future of supply chain management, making it more secure, efficient, and sustainable.

3. Challenges in Renewable Energy Supply Chains

The integration of blockchain technology in renewable energy supply chains holds immense promise for enhancing transparency, security, and traceability. However, several challenges need to be addressed to ensure its effective implementation. These challenges are often related to the complexity of tracking materials, ensuring compliance with governance standards, preventing fraud and data manipulation, and providing real-time monitoring of assets.

One of the key challenges faced in renewable energy supply chains is the complexity of tracking and verifying the origin of materials used in the manufacturing of solar panels, wind turbines, and batteries. The renewable energy sector relies on various raw materials, such as rare earth metals, silicon, and lithium, which are sourced from different regions across the globe (Abdelaal, Elkatatny & Abdulraheem, 2021, Epelle & Gerogiorgis, 2020, Misra, et al., 2022). These materials often pass through multiple stages of extraction, refinement, and manufacturing before reaching their final destination. The long and complex journey of these materials makes it difficult to track their origin and ensure that they meet the necessary sustainability and ethical standards.

Blockchain technology could potentially address this issue by providing a transparent and immutable record of every transaction involving the materials throughout the supply chain. However, the challenge lies in ensuring that every participant in the chain, from miners to manufacturers to distributors, records accurate and truthful data. In many cases, stakeholders in different parts of the supply chain may not have the incentive or the infrastructure to participate fully in a blockchain network (Khalid, et al., 2016, Kiran, et al., 2017, Li, et al., 2019, Marhoon, 2020, Nimana, Canter & Kumar, 2015). Furthermore, some raw materials are sourced from regions with limited oversight or where traceability mechanisms are underdeveloped. Ensuring that all stakeholders in the supply chain adhere to blockchain protocols and accurately record the origin of materials is a significant challenge that requires collaboration, standardization, and infrastructure development.

Another significant challenge is ensuring compliance with environmental and social governance (ESG) standards across the entire supply chain. Renewable energy projects are under increasing scrutiny from consumers, regulators, and investors who expect companies to uphold high standards of sustainability, labor practices, and social responsibility (AlBahrani, et al., 2022, Cordes, et al., 2016, Ericson, Engel-Cox & Arent, 2019, Zabbey & Olsson, 2017). Blockchain offers a promising solution for tracking compliance with ESG standards, but verifying adherence across diverse supply chains can be difficult. For example, companies may face challenges in ensuring that mining operations for critical raw materials like cobalt and lithium are carried out responsibly, with minimal environmental impact and fair labor practices. In many cases, these operations occur in regions with lax regulatory oversight, making it difficult to ensure that suppliers are compliant with established standards.

Blockchain can help by providing a transparent record of all transactions, making it easier for companies to track the source and journey of raw materials and verify their compliance with ESG criteria. However, for this system to be effective, it requires active participation from all stakeholders, including those at the beginning of the supply chain, such as mining companies. This can be challenging, particularly when dealing with international supply chains that involve multiple jurisdictions and regulatory environments (Suvin, et al., 2021, Van Oort,et al., 2021, Wilberforce, et al., 2019, Yudha, Tjahjono & Longhurst, 2022). Additionally, ensuring that blockchain data accurately reflects ESG compliance requires robust auditing and verification mechanisms, which may not always be readily available in the regions where raw materials are sourced. Without the proper auditing infrastructure and a commitment from all players in the supply chain to uphold ESG standards, blockchain's potential for improving compliance could be limited.

Fraud, theft, and data manipulation represent another significant challenge in blockchain-based supply chains. While blockchain's immutability and cryptographic security features make it highly resistant to tampering, the technology is not immune to all forms of manipulation. For instance, if data is entered incorrectly or fraudulently at the point of origin, the integrity of the entire supply chain could be compromised (Ozowe, Zheng & Sharma, 2020, Pereira, et al., 2022, Seyedmohammadi, 2017, Stober & Bucher, 2013). This could occur when materials are misrepresented, or counterfeit products are introduced into the system. For example, counterfeit solar panels or wind turbines could be sold as genuine products if their data is falsely entered into the blockchain.

Fraudulent practices can also arise during the transportation and storage phases of the supply chain. Even though blockchain can record every transaction and transfer of goods, the physical security of assets in transit remains a concern. Theft can still occur, and blockchain alone cannot prevent it from happening. While blockchain can help to

track goods once they enter the system, its effectiveness in preventing theft or fraud relies heavily on the security of physical assets and the integrity of data entry (Adejugbe & Adejugbe, 2015, Okeke, et al., 2022, Erofeev, et al., 2019, Mohsen & Fereshteh, 2017). As such, a multi-layered approach that combines blockchain technology with physical security measures such as RFID tags, sensors, and surveillance will be essential to mitigate these risks.

Data manipulation is also a concern in blockchain systems. While the technology provides a transparent and immutable ledger, it depends on accurate data input. If bad data is entered into the system at any point, it becomes part of the permanent record, which could distort the entire chain of custody for renewable energy products. For example, if a supplier misreports the origin of raw materials or falsifies compliance data, the blockchain cannot independently verify the truthfulness of the information (Ahlstrom, et al., 2020, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Najibi, et al., 2017). Blockchain systems can only reflect what is input into them, meaning that ensuring the accuracy and authenticity of the data is critical to their success. To address this challenge, strong verification systems and third-party audits are necessary to ensure that data is accurate and reliable before being added to the blockchain.

The lack of real-time monitoring and asset tracking is another challenge faced in the renewable energy supply chain. While blockchain offers transparency and traceability, its implementation for real-time monitoring can be difficult due to the complexity of the supply chain and the diverse actors involved. In the renewable energy sector, assets such as solar panels, wind turbines, and energy storage systems may move across long distances, pass through various distribution channels, and undergo numerous stages of handling before they are installed and operational. Tracking these assets in real-time is essential for improving operational efficiency, reducing delays, and ensuring that the assets are in the right place at the right time.

Although blockchain can provide a historical record of transactions, real-time monitoring requires integrating blockchain with other technologies such as Internet of Things (IoT) sensors, GPS tracking, and artificial intelligence. IoT devices can provide real-time data on the condition and location of assets, while GPS tracking systems can monitor the movement of goods across the supply chain (Abdelfattah, et al., 2021, Craddock, 2018, Eshiet & Sheng, 2018, Martin-Roberts, et al., 2021). When combined with blockchain, these technologies can enable real-time asset tracking, providing greater visibility and control over the supply chain. However, the challenge lies in the integration of these technologies into existing supply chain infrastructure, particularly in regions where IoT and GPS systems are not widely used or reliable. Furthermore, ensuring that real-time data is accurately captured and recorded in the blockchain system is essential for maintaining the integrity of the supply chain and preventing errors or inconsistencies.

In conclusion, while blockchain offers significant potential for improving the transparency and security of renewable energy supply chains, several challenges must be addressed for its successful implementation. These include the complexity of tracking and verifying the origin of materials, ensuring compliance with ESG standards, preventing fraud and data manipulation, and integrating real-time monitoring and asset tracking. Overcoming these challenges will require collaboration across stakeholders, investment in infrastructure, and the development of robust verification systems. By addressing these issues, blockchain technology can help create more efficient, transparent, and secure renewable energy supply chains, supporting the growth of a sustainable and responsible energy sector.

4. Blockchain Applications in Renewable Energy Supply Chains

Blockchain technology has emerged as a powerful tool for enhancing transparency, security, and efficiency in various industries, including renewable energy. As the world transitions toward cleaner energy sources, the need for transparent, secure, and efficient supply chain management in the renewable energy sector has become more critical. Blockchain, with its decentralized and immutable nature, offers a promising solution to address these challenges. By ensuring the ethical sourcing of materials, tracking products in real-time, automating transactions through smart contracts, integrating Internet of Things (IoT) data, and improving predictive maintenance and asset management, blockchain can revolutionize renewable energy supply chains.

One of the primary applications of blockchain in renewable energy supply chains is material traceability and verification. Renewable energy technologies, such as solar panels, wind turbines, and energy storage systems, rely on raw materials like rare earth metals, cobalt, and lithium. These materials are often mined in countries with weak governance structures and limited environmental oversight, raising concerns about the ethical and sustainable sourcing of these materials (Olufemi, Ozowe & Afolabi, 2012, Ozowe, 2021, Quintanilla, et al., 2021, Shortall, Davidsdottir & Axelsson, 2015). Blockchain technology can address these concerns by enabling the traceability and verification of raw materials used in renewable energy products. By recording every transaction and movement of materials on a blockchain, companies can ensure that materials are sourced ethically and sustainably, reducing the risk of human

rights violations, environmental damage, and fraud. This traceability not only provides transparency for consumers but also helps businesses comply with increasingly stringent regulations on supply chain responsibility.

In addition to ensuring ethical sourcing, blockchain enables real-time tracking and transparency throughout the entire lifecycle of renewable energy products. From production to deployment, blockchain can track products as they move through the supply chain, providing an immutable record of every step. This transparency allows stakeholders to verify the authenticity and quality of products, helping to reduce fraud and counterfeiting. For example, when a solar panel is manufactured and shipped to a project site, blockchain can track its movement, ensuring that it is the correct product and that it meets all required quality standards (Jomthanachai, Wong & Lim, 2021, Li, et al., 2022, Luo, et al., 2019, Mosca, et al., 2018). Furthermore, blockchain's real-time tracking capabilities can help prevent delays, optimize logistics, and ensure that renewable energy projects are completed on time and within budget. By providing a transparent and tamper-proof record of transactions, blockchain can foster trust among stakeholders, including manufacturers, suppliers, and consumers, and reduce the risks associated with fraud and mismanagement.

Blockchain also plays a vital role in automating transactions and ensuring compliance through the use of smart contracts. Smart contracts are self-executing contracts with the terms of the agreement directly written into code. In the context of renewable energy supply chains, smart contracts can automate various processes, such as payments, deliveries, and compliance checks, reducing the need for paperwork and intermediaries. For example, when a renewable energy project reaches a certain milestone, a smart contract can automatically release payment to the supplier, ensuring timely and secure transactions (Agupugo, et al., 2022, Dagunduro & Adenugba, 2020, Okeke, et al., 2022, Nduagu & Gates, 2015). Additionally, smart contracts can help enforce compliance with regulations by automatically verifying that all parties meet the required standards before executing a transaction. This automation not only reduces administrative costs and the potential for human error but also enhances the efficiency and reliability of the supply chain. By eliminating the need for intermediaries and ensuring that all parties adhere to the terms of the contract, smart contracts help create a more streamlined and secure supply chain process.

Another significant application of blockchain in renewable energy supply chains is the integration of IoT-enabled devices and real-time data recording. The renewable energy sector increasingly relies on IoT devices to monitor and manage assets, such as solar panels, wind turbines, and energy storage systems. These devices generate vast amounts of data, which can be used to optimize performance, predict maintenance needs, and improve energy efficiency. However, the security and integrity of this data are critical, as tampering with or falsifying data could lead to operational inefficiencies or safety hazards (Adeniran, et al., 2022, Efunniyi, et al., 2022, Eyinla, et al., 2021, Mrdjen & Lee, 2016). Blockchain technology can provide a secure and transparent way to record real-time data from IoT-enabled devices. By recording data on a blockchain, renewable energy companies can ensure that the information is tamper-proof and accessible to all authorized parties. For example, blockchain can record data on the performance of a solar panel or the condition of a wind turbine, enabling real-time monitoring and analysis. This integration of blockchain with IoT data can enhance decision-making, improve asset performance, and reduce the risk of fraud.

Blockchain's potential in renewable energy supply chains extends beyond data recording to predictive maintenance and asset management. Renewable energy assets, such as wind turbines and solar panels, require regular maintenance to ensure optimal performance and minimize downtime. Blockchain can help improve asset management by providing a secure and transparent record of all maintenance activities, repairs, and upgrades. This record can be used to track the health of assets, predict when maintenance is needed, and ensure that maintenance is performed according to the manufacturer's guidelines (Suzuki, et al., 2022, Ugwu, 2015, Vielma & Mosti, 2014, Wojtanowicz, 2016, Zhang, et al., 2021). By leveraging blockchain for predictive maintenance, companies can reduce operational costs, increase the lifespan of assets, and improve overall system efficiency. Additionally, blockchain can help companies manage the lifecycle of renewable energy assets more effectively, ensuring that assets are properly maintained, replaced, or decommissioned at the appropriate time. This can lead to better operational efficiency and a more sustainable renewable energy infrastructure.

The integration of blockchain technology in renewable energy supply chains offers several benefits, including enhanced transparency, security, and efficiency. By ensuring the ethical sourcing of materials, providing real-time tracking, automating transactions through smart contracts, integrating IoT data, and improving predictive maintenance and asset management, blockchain can help create a more sustainable and resilient renewable energy ecosystem (Adenugba & Dagunduro, 2019, Elujide, et al., 2021, Okeke, et al., 2022, Njuguna, et al., 2022). As the renewable energy industry continues to grow, blockchain has the potential to play a central role in transforming supply chain management, driving innovation, and accelerating the transition to a cleaner, more sustainable energy future. The adoption of blockchain in renewable energy supply chains not only benefits businesses by improving operational efficiency and reducing costs but also contributes to environmental sustainability and social responsibility. As technology continues to evolve, the

integration of blockchain into renewable energy supply chains will likely become a critical component of the industry's success.

5. Case Studies and Real-World Applications

Blockchain technology is rapidly gaining traction across various sectors, including renewable energy, due to its ability to provide transparent, secure, and efficient solutions for supply chain management. As renewable energy continues to grow as a key component of global energy systems, the need for robust and reliable supply chain management becomes even more critical. Blockchain, with its decentralized and immutable nature, offers a powerful tool to address many of the challenges faced by renewable energy supply chains, including material traceability, fraud prevention, transaction automation, and real-time data recording. Several real-world applications and case studies demonstrate the transformative potential of blockchain in renewable energy, highlighting the technology's practical use and the lessons learned from these implementations.

One notable example of blockchain implementation in renewable energy is the collaboration between the energy company Power Ledger and the Australian renewable energy sector. Power Ledger, a blockchain-based platform, was developed to enable peer-to-peer energy trading. The platform allows consumers to buy and sell surplus renewable energy directly to and from each other, without relying on traditional energy retailers (Adejugbe & Adejugbe, 2020, Elujide, et al., 2021, Fakhari, 2022, Mikunda, et al., 2021). By using blockchain to track and verify energy transactions, Power Ledger ensures transparency and security, providing consumers with real-time data about energy generation and consumption. This decentralization of energy trading allows individuals to become active participants in the renewable energy market, promoting the use of solar power and other clean energy sources. Power Ledger's platform also reduces administrative costs and eliminates intermediaries, resulting in lower transaction fees for consumers. This case study highlights the potential of blockchain to enable more efficient and transparent energy markets while also empowering consumers to take control of their energy use.

In the United States, the collaboration between the blockchain startup, IBM, and the multinational technology company, Maersk, illustrates how blockchain can be used to optimize supply chains in the renewable energy sector. IBM and Maersk developed the TradeLens blockchain platform, which aims to digitize and streamline global supply chain processes, including the transportation of renewable energy components such as wind turbines and solar panels. The platform provides a transparent and secure record of each step in the transportation process, from production to delivery, ensuring that all parties involved can track the movement of goods in real time (Ozowe, et al., 2020, Radwan, 2022, Salam & Salam, 2020, Shaw & Mukherjee, 2022). By using blockchain to record every transaction and movement, TradeLens eliminates the need for paper-based documentation, reducing delays and the risk of fraud. In the renewable energy sector, this technology can be particularly useful for ensuring the timely delivery of critical components and verifying their authenticity. The success of TradeLens in the renewable energy supply chain underscores the potential of blockchain to increase supply chain efficiency, reduce costs, and ensure the secure and transparent movement of goods.

Another example of blockchain implementation in renewable energy is the collaboration between the energy company Enel and the blockchain startup, Everledger, which focuses on improving the traceability of materials used in renewable energy technologies. Enel, one of the largest renewable energy companies in the world, partnered with Everledger to use blockchain technology to track the sourcing and production of the raw materials used in solar panels and wind turbines, such as cobalt and lithium. By recording every step of the supply chain on a blockchain, Enel can ensure that these materials are sourced ethically and sustainably, helping to address concerns about child labor, environmental degradation, and unethical practices in the mining industry. This traceability also provides transparency to consumers and investors, assuring them that the renewable energy technologies they are using or investing in are produced responsibly. The partnership between Enel and Everledger demonstrates how blockchain can be used to enhance the ethical and sustainable sourcing of materials in the renewable energy supply chain, while also promoting transparency and accountability.

In the field of wind energy, the company Vestas has explored blockchain to improve the management of its global supply chain, particularly in relation to the transportation and maintenance of wind turbines. Vestas partnered with the blockchain company Circularise to create a blockchain-based platform to track the lifecycle of wind turbine components, ensuring that materials are reused, recycled, and disposed of responsibly (Ahmad, et al., 2022, Waswa, Kedi & Sula, 2015, Farajzadeh, et al., 2022, Najibi & Asef, 2014). The platform also provides a secure and transparent record of all maintenance and repair activities, enabling Vestas to optimize the performance and longevity of its turbines. By using blockchain to manage its supply chain and operations more efficiently, Vestas aims to reduce costs, improve sustainability, and increase the overall effectiveness of its wind energy projects. This case study illustrates how

blockchain can be applied to wind energy to streamline supply chain processes and improve asset management, ultimately supporting the growth of renewable energy infrastructure.

Blockchain technology also plays a crucial role in automating transactions and reducing the administrative burden associated with renewable energy supply chains. In 2020, the energy company TotalEnergies implemented a blockchain-based solution to automate and verify renewable energy certificates in the European market. Renewable energy certificates (RECs) are used to prove that electricity has been generated from renewable sources, and they are often traded on a market to ensure that companies meet their renewable energy targets (Ali, et al., 2022, Beiranvand & Rajaee, 2022, Farajzadeh, et al., 2022, Mushtaq, et al., 2020). TotalEnergies used blockchain to create a secure and transparent system for issuing and trading RECs, reducing the administrative complexity and potential for fraud associated with paper-based systems. The use of blockchain ensures that each certificate is unique and cannot be tampered with, providing a more reliable and efficient system for tracking renewable energy generation. This initiative highlights how blockchain can streamline regulatory compliance and improve the transparency and security of renewable energy markets.

Success stories from these case studies offer valuable lessons for other organizations looking to implement blockchain in renewable energy supply chains. One key lesson is the importance of collaboration and partnerships between various stakeholders, including energy companies, technology providers, and supply chain partners (Kabeyi, 2019, Kumari & Ranjith, 2019, Li & Zhang, 2018, Mac Kinnon, Brouwer & Samuelsen, 2018). In many of the examples above, the successful implementation of blockchain relied on collaboration between different players in the renewable energy ecosystem, enabling them to pool resources, share knowledge, and develop comprehensive solutions. Another important lesson is the need for scalability and flexibility. Many of the blockchain platforms discussed, such as Power Ledger and TradeLens, were designed to be scalable, allowing them to accommodate the growing demands of the renewable energy sector. This scalability is crucial for ensuring that blockchain solutions can adapt to the evolving needs of the industry and continue to deliver value as renewable energy markets expand.

Industry partnerships and collaborations are also vital for overcoming the technical and regulatory challenges associated with blockchain adoption. In many cases, blockchain implementations have required navigating complex regulatory environments and aligning stakeholders with differing priorities and goals (Alagorni, Yaacob & Nour, 2015, Okeke, et al., 2022, Popo-Olaniyan, et al., 2022, Spada, Sutra & Burgherr, 2021). Successful partnerships have been essential for ensuring that blockchain solutions meet the requirements of governments, regulators, and consumers. For example, the partnership between IBM and Maersk was instrumental in gaining the trust of global shipping and logistics providers, while the collaboration between Enel and Everledger helped address the specific needs of renewable energy companies looking to ensure the ethical sourcing of materials. These collaborations highlight the importance of working together to overcome the challenges of blockchain integration and to create solutions that benefit all stakeholders in the renewable energy supply chain.

Blockchain is transforming the way renewable energy supply chains are managed by providing secure, transparent, and efficient solutions for tracking materials, automating transactions, and improving asset management. Real-world applications, such as those from Power Ledger, IBM, Maersk, Enel, and Vestas, demonstrate the immense potential of blockchain to revolutionize the renewable energy sector. By fostering collaboration, ensuring material traceability, and enhancing the efficiency of supply chain processes, blockchain can help accelerate the transition to a cleaner, more sustainable energy future.

6. Challenges and Limitations of Blockchain in Renewable Energy

Blockchain technology has garnered significant attention for its potential to enhance transparency and security in supply chain management across various sectors, including renewable energy. By offering decentralized, immutable ledgers, blockchain can address several critical challenges in renewable energy supply chains, such as ensuring material traceability, enhancing fraud prevention, and automating transactions. However, despite its promise, the implementation of blockchain in the renewable energy sector is not without its challenges. These challenges range from technical issues like scalability and interoperability to regulatory hurdles and adoption barriers from various stakeholders. Understanding and addressing these limitations is crucial for realizing the full potential of blockchain in renewable energy.

One of the foremost technical challenges facing the adoption of blockchain in renewable energy supply chains is scalability. While blockchain has demonstrated its value in small-scale applications, it is often criticized for its inability to handle large volumes of transactions efficiently. This is particularly relevant for the renewable energy sector, where supply chains can involve numerous parties, transactions, and data points. For instance, blockchain networks like

Bitcoin and Ethereum, which use proof-of-work consensus mechanisms, are notorious for their slow transaction speeds and high energy consumption (Adejugbe & Adejugbe, 2016, Gil-Ozoudeh, et al., 2022, Garia, et al., 2019, Nguyen, et al., 2014). The issue of scalability becomes even more pressing in a global supply chain context, where a blockchain network would need to accommodate millions of transactions across various geographic locations. As the renewable energy industry continues to expand, with increasing levels of decentralized energy production and consumption, the need for a blockchain system capable of handling vast amounts of data in real time is paramount.

In addition to scalability, interoperability presents another significant technical challenge. The renewable energy sector operates across diverse regions and systems, each with its own set of standards, technologies, and stakeholders. For blockchain to be effectively integrated into renewable energy supply chains, it must be able to communicate and exchange data seamlessly with existing systems, whether those are government databases, utility company platforms, or other digital infrastructure (Szulecki & Westphal, 2014, Thomas, et al., 2019, Udegbunam, 2015), Yu, Chen & Gu, 2020. However, blockchain's decentralized nature means that different blockchain platforms may operate using incompatible protocols, leading to fragmentation and difficulties in data sharing. This lack of interoperability could hinder the widespread adoption of blockchain and limit its ability to create an integrated, global renewable energy supply chain. Overcoming these technical barriers requires the development of standardized protocols and frameworks that enable blockchain platforms to work together and share data in a secure and efficient manner.

Beyond technical challenges, regulatory and legal considerations also play a significant role in limiting the widespread adoption of blockchain in renewable energy supply chains. Blockchain technology is still relatively new, and many countries have yet to establish clear regulations governing its use (Adland, Cariou & Wolff, 2019, Oyeniran, et al., 2022, Jafarizadeh, et al., 2022, Shrestha, et al., 2017). This regulatory uncertainty can create risks for companies seeking to implement blockchain solutions, as they may face legal challenges related to data privacy, intellectual property, and cross-border transactions. In the renewable energy sector, regulatory frameworks are already complex due to the need to comply with a variety of environmental, safety, and financial regulations. The introduction of blockchain adds another layer of complexity, as governments and regulators must adapt existing legal frameworks to accommodate new technologies.

Data privacy is one area where blockchain faces particular scrutiny. In many countries, strict data protection laws, such as the General Data Protection Regulation (GDPR) in the European Union, place limitations on how personal data can be stored and processed. Since blockchain is designed to be immutable, once data is recorded, it cannot be altered or deleted. This poses a potential conflict with data privacy regulations that require individuals to have the right to erase their personal data. In the renewable energy sector, where sensitive customer data might be stored on blockchain, ensuring compliance with privacy laws is a significant concern (Agemar, Weber & Schulz, 2014, Okeke, et al., 2022, Ghani, Khan & Garaniya, 2015, Sowiżdżał, Starczewska & Papiernik, 2022). To mitigate these risks, blockchain solutions must incorporate features such as off-chain data storage and encryption to balance the need for transparency with the protection of personal information.

Moreover, blockchain's cross-border nature introduces complications related to international law and jurisdiction. Renewable energy supply chains often span multiple countries, each with its own set of laws and regulations. Blockchain transactions, however, are not confined by national borders, and this can create legal challenges regarding the enforcement of contracts, dispute resolution, and intellectual property rights (Ahmad, et al., 2021, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Maraveas, et al., 2022). As renewable energy supply chains grow more globalized, these issues will need to be addressed through international cooperation and harmonization of regulatory standards. Until such global legal frameworks are established, blockchain-based solutions in renewable energy may face significant legal and regulatory hurdles that limit their effectiveness.

In addition to technical and regulatory challenges, adoption barriers from stakeholders also present a significant obstacle to the widespread implementation of blockchain in renewable energy supply chains. The renewable energy sector is composed of a wide range of stakeholders, including energy producers, utility companies, equipment manufacturers, regulators, and consumers. For blockchain to be successful, all these parties must be willing to adopt and integrate the technology into their operations (Ozowe, Russell & Sharma, 2020, Rahman, Canter & Kumar, 2014, Rashid, Benhelal & Rafiq, 2020). However, many stakeholders in the renewable energy industry are still unfamiliar with blockchain and its potential benefits, which can lead to resistance to adoption. For instance, energy producers and utility companies may be hesitant to invest in blockchain technology if they perceive it as an unproven or costly solution. Similarly, regulators may be reluctant to approve blockchain-based systems without a clear understanding of how they will interact with existing regulatory frameworks.

Another adoption barrier stems from the legacy systems currently in use within the renewable energy sector. Many companies rely on outdated, paper-based systems or centralized databases that have been in place for years. Transitioning to a blockchain-based system would require significant investment in new infrastructure and training for employees, which can be a major deterrent for organizations, particularly those operating in emerging markets with limited resources (Abdo, 2019, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Glassley, 2014, Soltani, et al., 2021). Moreover, there is a general lack of standards and best practices for implementing blockchain in renewable energy supply chains, making it difficult for companies to determine how to proceed. This uncertainty around implementation and integration can slow down the adoption process and limit the potential impact of blockchain in the industry.

Furthermore, the energy sector has long been dominated by large, centralized players, such as major utility companies, which may be resistant to adopting a decentralized system like blockchain. These companies may view blockchain as a threat to their business models, as it enables greater decentralization and disrupts traditional ways of doing business. For example, peer-to-peer energy trading platforms built on blockchain could reduce the need for traditional utility companies, who may lose out on revenue from energy distribution (Adejugbe & Adejugbe, 2019, de Almeida, Araújo & de Medeiros, 2017, Tula, et al., 2004). Such resistance from entrenched players in the industry could slow the adoption of blockchain and make it more difficult for new, decentralized energy solutions to gain traction.

The financial cost of implementing blockchain is another significant adoption barrier. Developing and maintaining a blockchain-based system can be expensive, particularly for small and medium-sized enterprises (SMEs) in the renewable energy sector. The cost of infrastructure, software development, and integration with existing systems can be prohibitive for companies operating on tight budgets. This financial barrier is especially problematic in regions where renewable energy is still in the early stages of development and companies lack the resources to invest in advanced technologies like blockchain.

In conclusion, while blockchain has the potential to revolutionize supply chain management in renewable energy by offering transparent, secure, and efficient solutions, several challenges and limitations must be addressed before it can be fully implemented. Technical challenges such as scalability and interoperability, coupled with regulatory and legal considerations, create significant obstacles to adoption. Additionally, resistance from stakeholders and the high costs of implementation further complicate the integration of blockchain in renewable energy supply chains (Adenugba, Excel & Dagunduro, 2019, Child, et al., 2018, Huaman & Jun, 2014, Soeder & Soeder, 2021). Overcoming these barriers will require collaboration between industry players, regulators, and technology providers, as well as a concerted effort to develop scalable, interoperable, and legally compliant blockchain solutions. With continued innovation and cooperation, blockchain has the potential to play a transformative role in enhancing the efficiency, transparency, and sustainability of renewable energy supply chains.

7. Future Outlook and Opportunities

Blockchain technology holds tremendous potential to reshape the renewable energy sector by improving the transparency, security, and efficiency of supply chain management. As the world increasingly shifts toward sustainable energy solutions, blockchain can play a key role in addressing some of the sector's most pressing challenges. These include ensuring the ethical sourcing of materials, reducing fraud, enhancing operational efficiency, and driving sustainability (Tahmasebi, et al., 2020, Teodoriu & Bello, 2021, Wang, et al., 2018, Wu, et al., 2021). The future outlook for blockchain in renewable energy is highly promising, with emerging trends and technological advancements paving the way for more innovative and scalable solutions. Furthermore, there are significant opportunities for industry stakeholders to collaborate in accelerating the adoption of blockchain and unlocking its full potential.

One of the primary opportunities for blockchain in renewable energy lies in its ability to drive sustainability and innovation. As the renewable energy sector grows and evolves, the demand for transparent, secure, and efficient supply chains becomes more urgent. Blockchain offers a decentralized, immutable ledger that can track and verify every stage of the supply chain, from the sourcing of raw materials to the final deployment of renewable energy systems (Agu, et al., 2022, Diao & Ghorbani, 2018, Gil-Ozoudeh, et al., 2022, Mohd Aman, Shaari & Ibrahim, 2021). This ensures that all participants in the supply chain, including manufacturers, suppliers, and consumers, have access to reliable and verified information about the products they are using or purchasing. For instance, blockchain can help verify that the materials used in solar panels and wind turbines are ethically sourced, free from human rights violations, and produced in an environmentally sustainable manner. By ensuring the traceability and transparency of supply chains, blockchain can help foster trust among stakeholders and promote more sustainable practices across the renewable energy sector.

In addition to material traceability, blockchain can also help improve the efficiency of energy generation and distribution, driving innovation in the sector. By enabling the automation of transactions through smart contracts,

blockchain can streamline operations, reduce administrative costs, and eliminate inefficiencies in energy markets. This can benefit both energy producers and consumers, as blockchain-enabled systems can automatically verify and settle transactions, reducing the need for intermediaries and manual processing. Moreover, blockchain's decentralized nature allows for the creation of peer-to-peer energy trading platforms, where consumers can buy and sell excess energy directly with one another. This could transform the way energy is distributed, making the system more democratic and decentralized, and empowering individuals and communities to take control of their energy consumption and production (Adejugbe & Adejugbe, 2019, Govender, et al., 2022, Okeke, et al., 2022, Raliya, et al., 2017). The combination of transparency, efficiency, and security offered by blockchain can be a powerful catalyst for innovation in the renewable energy sector.

Emerging technologies such as artificial intelligence (AI), machine learning (ML), and big data offer further opportunities to enhance blockchain's capabilities in the renewable energy supply chain. The integration of AI and blockchain can lead to the creation of smart, autonomous systems that can optimize energy production, consumption, and distribution in real time. For example, AI algorithms could analyze data from blockchain-based energy platforms to predict energy demand patterns, identify inefficiencies, and recommend solutions to improve system performance. Machine learning models could also be used to analyze vast amounts of data generated by renewable energy assets, such as solar panels and wind turbines, to predict maintenance needs and reduce downtime (Karad & Thakur, 2021, Leung, et al., 2014, Liu, et al., 2019, Mahmood, et al., 2022). By combining AI and blockchain, energy systems can become more responsive, adaptable, and efficient, enabling faster decision-making and greater optimization of resources.

Big data analytics can also enhance blockchain's impact in renewable energy by providing deeper insights into supply chain operations and energy usage patterns. By analyzing large datasets, energy companies can gain valuable insights into trends, inefficiencies, and opportunities for improvement (Adejugbe & Adejugbe, 2018, Oyedokun, 2019, Hossain, et al., 2017, Jharap, et al., 2020). Blockchain can provide a secure and transparent platform for storing and sharing this data, enabling stakeholders to make data-driven decisions with confidence. For instance, energy producers can use big data to optimize their operations, track the performance of renewable energy assets, and identify potential areas for innovation. Similarly, consumers can use data to better understand their energy consumption patterns, make more informed decisions, and reduce their carbon footprint. By integrating blockchain with big data, the renewable energy sector can unlock new opportunities for improved sustainability, efficiency, and innovation.

The future of blockchain in renewable energy will also be shaped by opportunities for collaboration among industry stakeholders. Blockchain's potential to transform supply chain management and energy distribution requires the active participation of various players, including energy producers, suppliers, regulatory authorities, technology developers, and consumers (Tabatabaei, et al., 2022, Tester, et al., 2021, Weldeslassie, et al., 2018, Younger, 2015). Collaboration is essential to overcoming the technical, regulatory, and financial barriers that currently hinder the widespread adoption of blockchain. For instance, energy producers and utility companies will need to work together to integrate blockchain technology into existing infrastructure and ensure interoperability between different systems. Regulators and policymakers must also be involved in creating legal frameworks that support the use of blockchain while ensuring data privacy, security, and compliance with industry standards.

One of the key areas where collaboration is needed is the development of industry-wide standards and protocols for blockchain-based renewable energy systems. Without common standards, different blockchain platforms may struggle to communicate with one another, creating fragmentation in the market and limiting the ability to share data across borders. Industry stakeholders can work together to create interoperable blockchain solutions that can be adopted globally, making it easier for renewable energy companies to scale their operations and connect with other players in the industry (Agupugo & Tochukwu, 2021, Chenic, et al., 2022, Hoseinpour & Riahi, 2022, Raza, et al., 2019). By collaborating on standards, stakeholders can help foster a more unified and efficient blockchain ecosystem for the renewable energy sector.

Collaboration is also essential for driving the adoption of blockchain technology across the renewable energy value chain. Many stakeholders in the industry are still unfamiliar with blockchain and may be hesitant to invest in new technologies. By working together, industry players can share knowledge, resources, and best practices to promote the benefits of blockchain and encourage wider adoption. For example, large utility companies, technology providers, and startups can form strategic partnerships to pilot blockchain projects and demonstrate their potential value in real-world applications (Adepoju, Esan & Akinyomi, 2022, Iwuanyanwu, et al., 2022, Griffiths, 2017, Soga, et al., 2016). These pilot projects can serve as proof of concept for the broader industry, showcasing how blockchain can enhance supply chain transparency, reduce costs, and improve operational efficiency. By collaborating on such initiatives, industry stakeholders can help build trust in blockchain and accelerate its adoption across the renewable energy sector.

Another area where collaboration could unlock significant opportunities is the development of blockchain-based financing models for renewable energy projects. Renewable energy projects often require substantial upfront investment, and securing financing can be a major barrier to project development. Blockchain technology can help address this challenge by enabling new financing mechanisms, such as tokenized assets, green bonds, and crowdfunding platforms (Adejugbe, 2021, Chen, et al., 2022, Chukwuemeka, Amede & Alfazazi, 2017, Muther, et al., 2022). Through blockchain, investors can securely participate in renewable energy projects, track their investments in real time, and receive automated payouts through smart contracts. By collaborating with financial institutions, renewable energy companies can explore innovative financing models that increase access to capital and support the growth of renewable energy projects worldwide.

As the renewable energy sector continues to evolve, blockchain has the potential to become an integral part of the industry's technological ecosystem. By enabling greater transparency, security, and efficiency, blockchain can drive sustainability, enhance innovation, and create new business models in renewable energy. The integration of emerging technologies like AI, ML, and big data will further enhance blockchain's capabilities, allowing for more intelligent and responsive energy systems (Adenugba & Dagunduro, 2018, Matthews, et al., 2018, Gür, 2022, Jamrozik, et al., 2016). However, to realize blockchain's full potential, collaboration among industry stakeholders is essential. By working together to address technical, regulatory, and financial challenges, the renewable energy sector can unlock new opportunities for innovation and accelerate the adoption of blockchain technology, ultimately contributing to a more sustainable and decentralized energy future.

8. Conclusion

Blockchain technology holds significant promise in revolutionizing the renewable energy sector by enhancing transparency, security, and efficiency in supply chain management. Throughout its application in this field, blockchain has the potential to address critical challenges such as ethical material sourcing, fraud reduction, and inefficient energy distribution. By enabling real-time tracking, verifiable transactions, and the automation of operations through smart contracts, blockchain ensures that renewable energy supply chains are both more transparent and secure. The integration of Internet of Things (IoT) devices and predictive maintenance further optimizes the management and operation of renewable energy assets, enhancing their performance and minimizing operational risks.

As blockchain continues to be explored and implemented in the renewable energy sector, its role in transforming supply chains cannot be overstated. It offers an unprecedented level of transparency, allowing stakeholders to track every step of the energy production and distribution process. This transparency fosters trust, ensuring that consumers, producers, and regulators are confident that products are ethically sourced, produced sustainably, and operate within compliance. Blockchain's ability to automate processes through smart contracts and reduce reliance on intermediaries further streamlines operations, reducing costs and improving overall efficiency. Furthermore, the integration of advanced technologies such as AI, machine learning, and big data analytics with blockchain opens new possibilities for real-time decision-making, predictive maintenance, and further optimization of energy systems.

Looking ahead, blockchain is poised to play a central role in driving the future of renewable energy. As the world continues its transition toward more sustainable energy solutions, blockchain provides a valuable tool for promoting sustainability, fostering innovation, and ensuring that supply chains in the renewable energy sector remain transparent, secure, and efficient. The potential for collaboration among industry stakeholders, coupled with the ongoing development of new technologies and regulatory frameworks, will be crucial in accelerating blockchain adoption. In this context, blockchain not only represents a technological advancement but also a fundamental shift in how the renewable energy industry can operate in a more sustainable and transparent manner, contributing to a greener and more decentralized energy future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

Reference

[1] Adejugbe, A. (2020). Comparison Between Unfair Dismissal Law in Nigeria and the International Labour Organization's Legal Regime. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.3697717

[2] Adejugbe, A., (2021). From Contract to Status: Unfair Dismissal Law. Nnamdi Azikiwe University Journal of Commercial and Property Law, 8(1), pp. 39-53. https://journals.unizik.edu.ng/jcpl/article/view/649/616

[3] Adejugbe, A., Adejugbe A. (2014). Cost and Event in Arbitration (Case Study: Nigeria). Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.2830454

[4] Adejugbe, A., Adejugbe A. (2015). Vulnerable Children Workers and Precarious Work in a Changing World in Nigeria. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.2789248

[5] Adejugbe, A., Adejugbe A. (2016). A Critical Analysis of the Impact of Legal Restriction on Management and Performance of an Organization Diversifying into Nigeria. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.2742385

[6] Adejugbe, A., Adejugbe A. (2018). Women and Discrimination in the Workplace: A Nigerian Perspective. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.3244971

[7] Adejugbe, A., Adejugbe A. (2019). Constitutionalisation of Labour Law: A Nigerian Perspective. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.3311225

[8] Adejugbe, A., Adejugbe A. (2019). The Certificate of Occupancy as a Conclusive Proof of Title: Fact or Fiction. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.3324775

[9] Adejugbe, A., Adejugbe A. (2020). The Philosophy of Unfair Dismissal Law in Nigeria. Social Science Research Network Electronic Journal. DOI:10.2139/ssrn.3697696

[10] Adejugbe, A., Adejugbe, A. (2018). Emerging Trends in Job Security: A Case Study of Nigeria (1st ed.). LAP LAMBERT Academic Publishing. https://www.amazon.com/Emerging-Trends-Job-Security-Nigeria/dp/6202196769

[11] Adeniran, A. I., Abhulimen, A. O., Obiki-Osafiele. A. N., Osundare, O. S., Efunniyi, C. P., Agu, E. E. (2022). Digital banking in Africa: A conceptual review of financial inclusion and socio-economic development. International Journal of Applied Research in Social Sciences, 2022, 04(10), 451-480, https://doi.org/10.51594/ijarss.v4i10.1480

[12] Adeniran, I. A, Abhulimen A.O, Obiki-Osafiele, A.N, Osundare O.S, Efunniyi C.P, & Agu E.E. (2022): Digital banking in Africa: A conceptual review of financial inclusion and socio-economic development. International Journal of Applied Research in Social Sciences, Volume 4, Issue 10, P.No. 451-480, 2022

[13] Adenugba, A. A & Dagunduro A. O (2021): Leadership style and Decision Making As Determinants of Employee Commitment in Local Governments in Nigeria: International Journal of Management Studies and Social Science Research (IJMSSSR), 3(4), 257-267https://www.ijmsssr.org/paper/IJMSSSR00418.pdf

[14] Adenugba, A. A, & Dagunduro, A.O. (2019). Collective Bargaining. In Okafor, E.E., Adetola, O.B, Aborisade, R. A. & Abosede, A. J (Eds.) (June, 2019). Human Resources: Industrial Relations and Management Perspectives. 89 – 104. ISBN 078-978-55747-2-2. (Nigeria)

[15] Adenugba, A. A, Dagunduro, A. O & Akhutie, R. (2018): An Investigation into the Effects of Gender Gap in Family Roles in Nigeria: The Case of Ibadan City. African Journal of Social Sciences (AJSS), 8(2), 37-47. https://drive.google.com/file/d/1eQa16xEF58KTmY6-8x4X8HDhk-K-JF1M/view

[16] Adenugba, A. A, Excel, K. O & Dagunduro, A.O (2019): Gender Differences in the Perception and Handling of Occupational Stress Among Workers in Commercial Banks in IBADAN, Nigeria: African Journal for the Psychological Studies of Social Issues (AJPSSI), 22(1), 133- 147. https://ajpssi.org/index.php/ajpssi/article/view/371

[17] Adepoju, O., Esan, O., & Akinyomi, O. (2022). Food security in Nigeria: enhancing workers' productivity in precision agriculture. Journal of Digital Food, Energy & Water Systems, 3(2).

[18] Aftab, A. A. R. I., Ismail, A. R., Ibupoto, Z. H., Akeiber, H., & Malghani, M. G. K. (2017). Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review. *Renewable and Sustainable Energy Reviews*, *76*, 1301-1313.

[19] Agemar, T., Weber, J., & Schulz, R. (2014). Deep geothermal energy production in Germany. *Energies*, *7*(7), 4397-4416.

[20] Agu, E.E, Abhulimen A.O, Obiki-Osafiele, A.N, Osundare O.S, Adeniran I.A & Efunniyi C.P. (2022): Artificial Intelligence in African Insurance: A review of risk management and fraud prevention. International Journal of Management & Entrepreneurship Research, Volume 4, Issue 12, P.No.768-794, 2022.

[21] Agupugo, C. P., & Tochukwu, M. F. C. (2021): A model to Assess the Economic Viability of Renewable Energy Microgrids: A Case Study of Imufu Nigeria.

[22] Agupugo, C. P., Ajayi, A. O., Nwanevu, C., & Oladipo, S. S. (2022); Advancements in Technology for Renewable Energy Microgrids.

[23] Agupugo, C. P., Ajayi, A. O., Nwanevu, C., & Oladipo, S. S. (2022): Policy and regulatory framework supporting renewable energy microgrids and energy storage systems.

[24] Ahlstrom, D., Arregle, J. L., Hitt, M. A., Qian, G., Ma, X., & Faems, D. (2020). Managing technological, sociopolitical, and institutional change in the new normal. *Journal of Management Studies*, *57*(3), 411-437.

[25] Ahmad, T., Madonski, R., Zhang, D., Huang, C., & Mujeeb, A. (2022). Data-driven probabilistic machine learning in sustainable smart energy/smart energy systems: Key developments, challenges, and future research opportunities in the context of smart grid paradigm. *Renewable and Sustainable Energy Reviews*, *160*, 112128.

[26] Ahmad, T., Zhang, D., Huang, C., Zhang, H., Dai, N., Song, Y., & Chen, H. (2021). Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. *Journal of Cleaner Production*, *289*, 125834.

[27] Akpan, E. U. (2019). *Water-based drilling fluids for high temperature and dispersible shale formation applications*. University of Salford (United Kingdom).

[28] Alagorni, A. H., Yaacob, Z. B., & Nour, A. H. (2015). An overview of oil production stages: enhanced oil recovery techniques and nitrogen injection. *International Journal of Environmental Science and Development*, *6*(9), 693.

[29] AlBahrani, H., Alsheikh, M., Wagle, V., & Alshakhouri, A. (2022, March). Designing Drilling Fluids Rheological Properties with a Numerical Geomechanics Model for the Purpose of Improving Wellbore Stability. In *SPE/IADC Drilling Conference and Exhibition* (p. D011S009R003). SPE.

[30] Ali, I., Ahmad, M., Arain, A. H., Atashbari, V., & Zamir, A. (2022). Utilization of Biopolymers in Water Based Drilling Muds. In *Drilling Engineering and Technology-Recent Advances New Perspectives and Applications*. IntechOpen.

[31] Bassey, K. E. (2022). Enhanced Design and Development Simulation and Testing. Engineering Science & Technology Journal, 3(2), 18-31.

[32] Bassey, K. E. (2022). Optimizing Wind Farm Performance Using Machine Learning. Engineering Science & Technology Journal, 3(2), 32-44.

[33] Beiranvand, B., & Rajaee, T. (2022). Application of artificial intelligence-based single and hybrid models in predicting seepage and pore water pressure of dams: A state-of-the-art review. *Advances in Engineering Software*, *173*, 103268.

[34] Bello, O. A., Folorunso, A., Ogundipe, A., Kazeem, O., Budale, A., Zainab, F., & Ejiofor, O. E. (2022). Enhancing Cyber Financial Fraud Detection Using Deep Learning Techniques: A Study on Neural Networks and Anomaly Detection. *International Journal of Network and Communication Research*, *7*(1), 90-113.

[35] Bristol-Alagbariya, B., Ayanponle, O. L., & Ogedengbe, D. E. (2022). Integrative HR approaches in mergers and acquisitions ensuring seamless organizational synergies. *Magna Scientia Advanced Research and Reviews*, *6*(01), 078–085. Magna Scientia Advanced Research and Reviews.

[36] Bristol-Alagbariya, B., Ayanponle, O. L., & Ogedengbe, D. E. (2022). Strategic frameworks for contract management excellence in global energy HR operations. *GSC Advanced Research and Reviews*, *11*(03), 150–157. GSC Advanced Research and Reviews.

[37] Bristol-Alagbariya, B., Ayanponle, O. L., & Ogedengbe, D. E. (2022). Developing and implementing advanced performance management systems for enhanced organizational productivity. *World Journal of Advanced Science and Technology*, *2*(01), 039–046. World Journal of Advanced Science and Technology.

[38] Chen, X., Cao, W., Gan, C., & Wu, M. (2022). A hybrid partial least squares regression-based real time pore pressure estimation method for complex geological drilling process. *Journal of Petroleum Science and Engineering*, *210*, 109771.

[39] Chenic, A. Ş., Cretu, A. I., Burlacu, A., Moroianu, N., Vîrjan, D., Huru, D., ... & Enachescu, V. (2022). Logical analysis on the strategy for a sustainable transition of the world to green energy—2050. Smart cities and villages coupled to renewable energy sources with low carbon footprint. *Sustainability*, *14*(14), 8622.

[40] Child, M., Koskinen, O., Linnanen, L., & Breyer, C. (2018). Sustainability guardrails for energy scenarios of the global energy transition. *Renewable and Sustainable Energy Reviews*, *91*, 321-334.

[41] Chukwuemeka, A. O., Amede, G., & Alfazazi, U. (2017). A Review of Wellbore Instability During Well Construction: Types, Causes, Prevention and Control. *Petroleum & Coal*, *59*(5).

[42] Cordes, E. E., Jones, D. O., Schlacher, T. A., Amon, D. J., Bernardino, A. F., Brooke, S., ... & Witte, U. (2016). Environmental impacts of the deep-water oil and gas industry: a review to guide management strategies. *Frontiers in Environmental Science*, *4*, 58.

[43] Craddock, H. A. (2018). *Oilfield chemistry and its environmental impact*. John Wiley & Sons.

[44] da Silva Veras, T., Mozer, T. S., & da Silva César, A. (2017). Hydrogen: trends, production and characterization of the main process worldwide. *International journal of hydrogen energy*, *42*(4), 2018-2033.

[45] Dagunduro A. O & Adenugba A. A (2020): Failure to Meet up to Expectation: Examining Women Activist Groups and Political Movements In Nigeria: De Gruyter; Open Cultural Studies 2020: 4, 23-35.

[46] de Almeida, P. C., Araújo, O. D. Q. F., & de Medeiros, J. L. (2017). Managing offshore drill cuttings waste for improved sustainability. *Journal of cleaner production*, *165*, 143-156.

[47] Diao, H., & Ghorbani, M. (2018). Production risk caused by human factors: a multiple case study of thermal power plants. *Frontiers of Business Research in China*, *12*, 1-27.

[48] Dickson, M. H., & Fanelli, M. (2018). What is geothermal energy?. In *Renewable Energy* (pp. Vol1_302-Vol1_328). Routledge.

[49] Dominy, S. C., O'Connor, L., Parbhakar-Fox, A., Glass, H. J., & Purevgerel, S. (2018). Geometallurgy—A route to more resilient mine operations. *Minerals*, *8*(12), 560.

[50] Dong, X., Liu, H., Chen, Z., Wu, K., Lu, N., & Zhang, Q. (2019). Enhanced oil recovery techniques for heavy oil and oilsands reservoirs after steam injection. *Applied energy*, *239*, 1190-1211.

[51] Dufour, F. (2018). The Costs and Implications of Our Demand for Energy: A Comparative and comprehensive Analysis of the available energy resources. *The Costs and Implications of Our Demand for Energy: A Comparative and Comprehensive Analysis of the Available Energy Resources (2018)*.

[52] Efunniyi, C.P, Abhulimen A.O, Obiki-Osafiele, A.N,Osundare O.S , Adeniran I.A , & Agu E.E. (2022): Data analytics in African banking: A review of opportunities and challenges for enhancing financial services. International Journal of Management & Entrepreneurship Research, Volume 4, Issue 12, P.No.748-767, 2022.3.

[53] El Bilali, A., Moukhliss, M., Taleb, A., Nafii, A., Alabjah, B., Brouziyne, Y., ... & Mhamed, M. (2022). Predicting daily pore water pressure in embankment dam: Empowering Machine Learning-based modeling. *Environmental Science and Pollution Research*, *29*(31), 47382-47398.

[54] Eldardiry, H., & Habib, E. (2018). Carbon capture and sequestration in power generation: review of impacts and opportunities for water sustainability. *Energy, Sustainability and Society*, *8*(1), 1-15.

[55] Elujide, I., Fashoto, S. G., Fashoto, B., Mbunge, E., Folorunso, S. O., & Olamijuwon, J. O. (2021). Application of deep and machine learning techniques for multi-label classification performance on psychotic disorder diseases. *Informatics in Medicine Unlocked*, *23*, 100545.

[56] Elujide, I., Fashoto, S. G., Fashoto, B., Mbunge, E., Folorunso, S. O., & Olamijuwon, J. O. Informatics in Medicine Unlocked.

[57] Epelle, E. I., & Gerogiorgis, D. I. (2020). A review of technological advances and open challenges for oil and gas drilling systems engineering. *AIChE Journal*, *66*(4), e16842.

[58] Ericson, S. J., Engel-Cox, J., & Arent, D. J. (2019). *Approaches for integrating renewable energy technologies in oil and gas operations* (No. NREL/TP-6A50-72842). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[59] Erofeev, A., Orlov, D., Ryzhov, A., & Koroteev, D. (2019). Prediction of porosity and permeability alteration based on machine learning algorithms. *Transport in Porous Media*, *128*, 677-700.

[60] Eshiet, K. I. I., & Sheng, Y. (2018). The performance of stochastic designs in wellbore drilling operations. *Petroleum Science*, *15*, 335-365.

[61] Eyinla, D. S., Oladunjoye, M. A., Olayinka, A. I., & Bate, B. B. (2021). Rock physics and geomechanical application in the interpretation of rock property trends for overpressure detection. *Journal of Petroleum Exploration and Production*, *11*, 75-95.

[62] Fakhari, N. (2022). *A mud design to improve water-based drilling in clay rich formation* (Doctoral dissertation, Curtin University).

[63] Farajzadeh, R., Eftekhari, A. A., Dafnomilis, G., Lake, L. W., & Bruining, J. (2020). On the sustainability of CO2 storage through CO2–Enhanced oil recovery. *Applied energy*, *261*, 114467.

[64] Farajzadeh, R., Glasbergen, G., Karpan, V., Mjeni, R., Boersma, D. M., Eftekhari, A. A., ... & Bruining, J. (2022). Improved oil recovery techniques and their role in energy efficiency and reducing CO2 footprint of oil production. *Journal of Cleaner Production*, *369*, 133308.

[65] Garia, S., Pal, A. K., Ravi, K., & Nair, A. M. (2019). A comprehensive analysis on the relationships between elastic wave velocities and petrophysical properties of sedimentary rocks based on laboratory measurements. *Journal of Petroleum Exploration and Production Technology*, *9*, 1869-1881.

[66] Ghani, A., Khan, F., & Garaniya, V. (2015). Improved oil recovery using CO 2 as an injection medium: a detailed analysis. *Journal of Petroleum Exploration and Production Technology*, *5*, 241-254.

[67] Gil-Ozoudeh, I., Iwuanyanwu, O., Okwandu, A. C., & Ike, C. S. (2022). *The role of passive design strategies in enhancing energy efficiency in green buildings*. Engineering Science & Technology Journal, Volume 3, Issue 2, December 2022, No.71-91

[68] Gil-Ozoudeh, I., Iwuanyanwu, O., Okwandu, A. C., & Ike, C. S. (2022). Life cycle assessment of green buildings: A comprehensive analysis of environmental impacts (pp. 729-747). Publisher. p. 730.

[69] Glassley, W. E. (2014). *Geothermal energy: renewable energy and the environment*. CRC press.

[70] Govender, P., Fashoto, S. G., Maharaj, L., Adeleke, M. A., Mbunge, E., Olamijuwon, J., ... & Okpeku, M. (2022). The application of machine learning to predict genetic relatedness using human mtDNA hypervariable region I sequences. *Plos one*, *17*(2), e0263790.

[71] Griffiths, S. (2017). A review and assessment of energy policy in the Middle East and North Africa region. *Energy Policy*, *102*, 249-269.

[72] Gür, T. M. (2022). Carbon dioxide emissions, capture, storage and utilization: Review of materials, processes and technologies. *Progress in Energy and Combustion Science*, *89*, 100965.

[73] Hoseinpour, M., & Riahi, M. A. (2022). Determination of the mud weight window, optimum drilling trajectory, and wellbore stability using geomechanical parameters in one of the Iranian hydrocarbon reservoirs. *Journal of Petroleum Exploration and Production Technology*, 1-20.

[74] Hossain, M. E., Al-Majed, A., Adebayo, A. R., Apaleke, A. S., & Rahman, S. M. (2017). A Critical Review of Drilling Waste Management Towards Sustainable Solutions. *Environmental Engineering & Management Journal (EEMJ)*, *16*(7).

[75] Huaman, R. N. E., & Jun, T. X. (2014). Energy related CO2 emissions and the progress on CCS projects: a review. *Renewable and Sustainable Energy Reviews*, *31*, 368-385.

[76] Iwuanyanwu, O., Gil-Ozoudeh, I., Okwandu, A. C., & Ike, C. S. (2022). *The integration of renewable energy systems in green buildings: Challenges and opportunities*. Journal of Applied

[77] Jafarizadeh, F., Rajabi, M., Tabasi, S., Seyedkamali, R., Davoodi, S., Ghorbani, H., ... & Csaba, M. (2022). Data driven models to predict pore pressure using drilling and petrophysical data. *Energy Reports*, *8*, 6551-6562.

[78] Jamrozik, A., Protasova, E., Gonet, A., Bilstad, T., & Żurek, R. (2016). Characteristics of oil based muds and influence on the environment. *AGH Drilling, Oil, Gas*, *33*(4).

[79] Jharap, G., van Leeuwen, L. P., Mout, R., van der Zee, W. E., Roos, F. M., & Muntendam-Bos, A. G. (2020). Ensuring safe growth of the geothermal energy sector in the Netherlands by proactively addressing risks and hazards. *Netherlands Journal of Geosciences*, *99*, e6.

[80] Jomthanachai, S., Wong, W. P., & Lim, C. P. (2021). An application of data envelopment analysis and machine learning approach to risk management. *Ieee Access*, *9*, 85978-85994.

[81] Kabeyi, M. J. B. (2019). Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, *5*(8), 53-95.

[82] Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Frontiers in Energy research*, *9*, 743114.

[83] Karad, S., & Thakur, R. (2021). Efficient monitoring and control of wind energy conversion systems using Internet of things (IoT): a comprehensive review. *Environment, development and sustainability*, *23*(10), 14197-14214.

[84] Khalid, P., Ahmed, N., Mahmood, A., Saleem, M. A., & Hassan. (2016). An integrated seismic interpretation and rock physics attribute analysis for pore fluid discrimination. *Arabian Journal for Science and Engineering*, *41*, 191-200.

[85] Kinik, K., Gumus, F., & Osayande, N. (2015). Automated dynamic well control with managed-pressure drilling: a case study and simulation analysis. *SPE Drilling & Completion*, *30*(02), 110-118.

[86] Kiran, R., Teodoriu, C., Dadmohammadi, Y., Nygaard, R., Wood, D., Mokhtari, M., & Salehi, S. (2017). Identification and evaluation of well integrity and causes of failure of well integrity barriers (A review). *Journal of Natural Gas Science and Engineering*, *45*, 511-526.

[87] Kumari, W. G. P., & Ranjith, P. G. (2019). Sustainable development of enhanced geothermal systems based on geotechnical research–A review. *Earth-Science Reviews*, *199*, 102955.

[88] Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and sustainable energy reviews*, *39*, 426-443.

[89] Li, G., Song, X., Tian, S., & Zhu, Z. (2022). Intelligent drilling and completion: a review. *Engineering*, *18*, 33-48.

[90] Li, H., & Zhang, J. (2018). Well log and seismic data analysis for complex pore-structure carbonate reservoir using 3D rock physics templates. *Journal of applied Geophysics*, *151*, 175-183.

[91] Li, W., Zhang, Q., Zhang, Q., Guo, F., Qiao, S., Liu, S., ... & Heng, X. (2019). Development of a distributed hybrid seismic–electrical data acquisition system based on the Narrowband Internet of Things (NB-IoT) technology. *Geoscientific Instrumentation, Methods and Data Systems*, *8*(2), 177-186.

[92] Lindi, O. (2017). *Analysis of Kick Detection Methods in the Light of Actual Blowout Disasters* (Master's thesis, NTNU).

[93] Liu, W., Zhang, G., Cao, J., Zhang, J., & Yu, G. (2019). Combined petrophysics and 3D seismic attributes to predict shale reservoirs favourable areas. *Journal of Geophysics and Engineering*, *16*(5), 974-991.

[94] Lohne, H. P., Ford, E. P., Mansouri, M., & Randeberg, E. (2016). Well integrity risk assessment in geothermal wells–Status of today. *GeoWell, Stavanger*.

[95] Luo, Y., Huang, H., Jakobsen, M., Yang, Y., Zhang, J., & Cai, Y. (2019). Prediction of porosity and gas saturation for deep-buried sandstone reservoirs from seismic data using an improved rock-physics model. *Acta Geophysica*, *67*, 557-575.

[96] Mac Kinnon, M. A., Brouwer, J., & Samuelsen, S. (2018). The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. *Progress in Energy and Combustion science*, *64*, 62-92.

[97] Mahmood, A., Thibodeaux, R., Angelle, J., & Smith, L. (2022, April). Digital transformation for promoting renewable energy & sustainability: A systematic approach for carbon footprint reduction in well construction. In *Offshore Technology Conference* (p. D031S038R005). OTC.

[98] Maraveas, C., Piromalis, D., Arvanitis, K. G., Bartzanas, T., & Loukatos, D. (2022). Applications of IoT for optimized greenhouse environment and resources management. *Computers and Electronics in Agriculture*, *198*, 106993.

[99] Marhoon, T. M. M. (2020). *High pressure High temperature (HPHT) wells technologies while drilling* (Doctoral dissertation, Politecnico di Torino).

[100] Martin, C. (2022). *Innovative drilling muds for High Pressure and High Temperature (HPHT) condition using a novel nanoparticle for petroleum engineering systems* (Doctoral dissertation).

[101] Martin-Roberts, E., Scott, V., Flude, S., Johnson, G., Haszeldine, R. S., & Gilfillan, S. (2021). Carbon capture and storage at the end of a lost decade. *One Earth*, *4*(11), 1569-1584.

[102] Matthews, V. O., Idaike, S. U., Noma-Osaghae, E., Okunoren, A., & Akwawa, L. (2018). Design and Construction of a Smart Wireless Access/Ignition Technique for Automobile. *International Journal for Research in Applied Science & Engineering Technology (IJRASET)*, *6*(8), 165-173.

[103] McCollum, D. L., Zhou, W., Bertram, C., De Boer, H. S., Bosetti, V., Busch, S., ... & Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy*, *3*(7), 589-599.

[104] Mikunda, T., Brunner, L., Skylogianni, E., Monteiro, J., Rycroft, L., & Kemper, J. (2021). Carbon capture and storage and the sustainable development goals. *International Journal of Greenhouse Gas Control*, *108*, 103318.

[105] Misra, S., Liu, R., Chakravarty, A., & Gonzalez, K. (2022). Machine learning tools for fossil and geothermal energy production and carbon geo-sequestration—a step towards energy digitization and geoscientific digitalization. *Circular Economy and Sustainability*, *2*(3), 1225-1240.

[106] Mohd Aman, A. H., Shaari, N., & Ibrahim, R. (2021). Internet of things energy system: Smart applications, technology advancement, and open issues. *International Journal of Energy Research*, *45*(6), 8389-8419.

[107] Mohsen, O., & Fereshteh, N. (2017). An extended VIKOR method based on entropy measure for the failure modes risk assessment–A case study of the geothermal power plant (GPP). *Safety science*, *92*, 160-172.

[108] Mosca, F., Djordjevic, O., Hantschel, T., McCarthy, J., Krueger, A., Phelps, D., ... & MacGregor, A. (2018). Pore pressure prediction while drilling: Three-dimensional earth model in the Gulf of Mexico. *AAPG Bulletin*, *102*(4), 691-708.

[109] Mrdjen, I., & Lee, J. (2016). High volume hydraulic fracturing operations: potential impacts on surface water and human health. *International journal of environmental health research*, *26*(4), 361-380.

[110] Mushtaq, N., Singh, D. V., Bhat, R. A., Dervash, M. A., & Hameed, O. B. (2020). Freshwater contamination: sources and hazards to aquatic biota. *Fresh water pollution dynamics and remediation*, 27-50.

[111] Muther, T., Syed, F. I., Lancaster, A. T., Salsabila, F. D., Dahaghi, A. K., & Negahban, S. (2022). Geothermal 4.0: AI-enabled geothermal reservoir development-current status, potentials, limitations, and ways forward. *Geothermics*, *100*, 102348.

[112] Najibi, A. R., & Asef, M. R. (2014). Prediction of seismic-wave velocities in rock at various confining pressures based on unconfined data. *Geophysics*, *79*(4), D235-D242.

[113] Najibi, A. R., Ghafoori, M., Lashkaripour, G. R., & Asef, M. R. (2017). Reservoir geomechanical modeling: In-situ stress, pore pressure, and mud design. *Journal of Petroleum Science and Engineering*, *151*, 31-39.

[114] Napp, T. A., Gambhir, A., Hills, T. P., Florin, N., & Fennell, P. S. (2014). A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renewable and Sustainable Energy Reviews*, *30*, 616-640.

[115] Nduagu, E. I., & Gates, I. D. (2015). Unconventional heavy oil growth and global greenhouse gas emissions. *Environmental science & technology*, *49*(14), 8824-8832.

[116] Nguyen, H. H., Khabbaz, H., Fatahi, B., Vincent, P., & Marix-Evans, M. (2014, October). Sustainability considerations for ground improvement techniques using controlled modulus columns. In *AGS Symposium on Resilient Geotechnics*. The Australian Geomechanics Society.

[117] Nimana, B., Canter, C., & Kumar, A. (2015). Energy consumption and greenhouse gas emissions in upgrading and refining of Canada's oil sands products. *Energy*, *83*, 65-79.

[118] Njuguna, J., Siddique, S., Kwroffie, L. B., Piromrat, S., Addae-Afoakwa, K., Ekeh-Adegbotolu, U., ... & Moller, L. (2022). The fate of waste drilling fluids from oil & gas industry activities in the exploration and production operations. *Waste Management*, *139*, 362-380.

[119] Okeke, C.I, Agu E.E, Ejike O.G, Ewim C.P-M and Komolafe M.O. (2022): A regulatory model for standardizing financial advisory services in Nigeria. International Journal of Frontline Research in Science and Technology, 2022, 01(02), 067–082.

[120] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). Developing a regulatory model for product quality assurance in Nigeria's local industries. International Journal of Frontline Research in Multidisciplinary Studies, 1(02), 54–69.

[121] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A service standardization model for Nigeria's healthcare system: Toward improved patient care. International Journal of Frontline Research in Multidisciplinary Studies, 1(2), 40–53.

[122] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A model for wealth management through standardized financial advisory practices in Nigeria. International Journal of Frontline Research in Multidisciplinary Studies, 1(2), 27–39.

[123] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A conceptual model for standardizing tax procedures in Nigeria's public and private sectors. International Journal of Frontline Research in Multidisciplinary Studies, 1(2), 14–26

[124] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A conceptual framework for enhancing product standardization in Nigeria's manufacturing sector. International Journal of Frontline Research in Multidisciplinary Studies, 1(2), 1–13.

[125] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). Modeling a national standardization policy for made-in-Nigeria products: Bridging the global competitiveness gap. International Journal of Frontline Research in Science and Technology, 1(2), 98–109.

[126] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A theoretical model for standardized taxation of Nigeria's informal sector: A pathway to compliance. International Journal of Frontline Research in Science and Technology, 1(2), 83–97.

[127] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A model for foreign direct investment (FDI) promotion through standardized tax policies in Nigeria. International Journal of Frontline Research in Science and Technology, 1(2), 53–66.

[128] Okeke, I. C., Agu, E. E., Ejike, O. G., Ewim, C. P., & Komolafe, M. O. (2022). A regulatory model for standardizing financial advisory services in Nigeria. International Journal of Frontline Research in Science and Technology, 1(2), 67–82.

[129] Okeke, I.C, Agu E.E, Ejike O.G, Ewim C.P-M and Komolafe M.O. (2022): A conceptual model for financial advisory standardization: Bridging the financial literacy gap in Nigeria. International Journal of Frontline Research in Science and Technology, 2022, 01(02), 038–052

[130] Okoroafor, E. R., Smith, C. M., Ochie, K. I., Nwosu, C. J., Gudmundsdottir, H., & Aljubran, M. J. (2022). Machine learning in subsurface geothermal energy: Two decades in review. *Geothermics*, *102*, 102401.

[131] Okwiri, L. A. (2017). *Risk assessment and risk modelling in geothermal drilling* (Doctoral dissertation).

[132] Olayiwola, T., & Sanuade, O. A. (2021). A data-driven approach to predict compressional and shear wave velocities in reservoir rocks. *Petroleum*, *7*(2), 199-208.

[133] Olufemi, B. A., Ozowe, W. O., & Komolafe, O. O. (2011). Studies on the production of caustic soda using solar powered diaphragm cells. *ARPN Journal of Engineering and Applied Sciences*, *6*(3), 49-54.

[134] Olufemi, B., Ozowe, W., & Afolabi, K. (2012). Operational Simulation of Sola Cells for Caustic. *Cell (EADC)*, *2*(6).

[135] Oyedokun, O. O. (2019). *Green human resource management practices and its effect on the sustainable competitive edge in the Nigerian manufacturing industry (Dangote)* (Doctoral dissertation, Dublin Business School).

[136] Oyeniran, C.O., Adewusi, A.O., Adeleke, A. G., Akwawa, L.A., Azubuko, C. F. (2022). Ethical AI: Addressing bias in machine learning models and software applications. Computer Science & IT Research Journal, 3(3), pp. 115-126

[137] Oyeniran, O. C., Adewusi, A. O., Adeleke, A. G., Akwawa, L. A., & Azubuko, C. F. (2022): Ethical AI: Addressing bias in machine learning models and software applications.

[138] Ozowe, W. O. (2018). *Capillary pressure curve and liquid permeability estimation in tight oil reservoirs using pressure decline versus time data* (Doctoral dissertation).

[139] Ozowe, W. O. (2021). *Evaluation of lean and rich gas injection for improved oil recovery in hydraulically fractured reservoirs* (Doctoral dissertation).

[140] Ozowe, W., Quintanilla, Z., Russell, R., & Sharma, M. (2020, October). Experimental evaluation of solvents for improved oil recovery in shale oil reservoirs. In *SPE Annual Technical Conference and Exhibition?* (p. D021S019R007). SPE.

[141] Ozowe, W., Russell, R., & Sharma, M. (2020, July). A novel experimental approach for dynamic quantification of liquid saturation and capillary pressure in shale. In *SPE/AAPG/SEG Unconventional Resources Technology Conference* (p. D023S025R002). URTEC.

[142] Ozowe, W., Zheng, S., & Sharma, M. (2020). Selection of hydrocarbon gas for huff-n-puff IOR in shale oil reservoirs. *Journal of Petroleum Science and Engineering*, *195*, 107683.

[143] Pan, S. Y., Gao, M., Shah, K. J., Zheng, J., Pei, S. L., & Chiang, P. C. (2019). Establishment of enhanced geothermal energy utilization plans: Barriers and strategies. *Renewable energy*, *132*, 19-32.

[144] Pereira, L. B., Sad, C. M., Castro, E. V., Filgueiras, P. R., & Lacerda Jr, V. (2022). Environmental impacts related to drilling fluid waste and treatment methods: A critical review. *Fuel*, *310*, 122301.

[145] Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). Future-Proofing human resources in the US with AI: A review of trends and implications. *International Journal of Management & Entrepreneurship Research*, *4*(12), 641-658.

[146] Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). A review of us strategies for stem talent attraction and retention: challenges and opportunities. *International Journal of Management & Entrepreneurship Research*, *4*(12), 588-606.

[147] Popo-Olaniyan, O., James, O. O., Udeh, C. A., Daraojimba, R. E., & Ogedengbe, D. E. (2022). Review of advancing US innovation through collaborative HR ecosystems: A sector-wide perspective. *International Journal of Management & Entrepreneurship Research*, *4*(12), 623-640.

[148] Quintanilla, Z., Ozowe, W., Russell, R., Sharma, M., Watts, R., Fitch, F., & Ahmad, Y. K. (2021, July). An experimental investigation demonstrating enhanced oil recovery in tight rocks using mixtures of gases and nanoparticles. In *SPE/AAPG/SEG Unconventional Resources Technology Conference* (p. D031S073R003). URTEC.

[149] Radwan, A. E. (2022). Drilling in complex pore pressure regimes: analysis of wellbore stability applying the depth of failure approach. *Energies*, *15*(21), 7872.

[150] Rahman, M. M., Canter, C., & Kumar, A. (2014). Greenhouse gas emissions from recovery of various North American conventional crudes. *Energy*, *74*, 607-617.

[151] Raliya, R., Saharan, V., Dimkpa, C., & Biswas, P. (2017). Nanofertilizer for precision and sustainable agriculture: current state and future perspectives. *Journal of agricultural and food chemistry*, *66*(26), 6487-6503.

[152] Rashid, M. I., Benhelal, E., & Rafiq, S. (2020). Reduction of greenhouse gas emissions from gas, oil, and coal power plants in Pakistan by carbon capture and storage (CCS): A Review. *Chemical Engineering & Technology*, *43*(11), 2140-2148.

[153] Raza, A., Gholami, R., Rezaee, R., Rasouli, V., & Rabiei, M. (2019). Significant aspects of carbon capture and storage–A review. *Petroleum*, *5*(4), 335-340.

[154] Salam, A., & Salam, A. (2020). Internet of things in sustainable energy systems. *Internet of Things for Sustainable Community Development: Wireless Communications, Sensing, and Systems*, 183-216.

[155] Seyedmohammadi, J. (2017). The effects of drilling fluids and environment protection from pollutants using some models. *Modeling Earth Systems and Environment*, *3*, 1-14.

[156] Shahbaz, M., Mallick, H., Mahalik, M. K., & Sadorsky, P. (2016). The role of globalization on the recent evolution of energy demand in India: Implications for sustainable development. *Energy Economics*, *55*, 52-68.

[157] Shahbazi, A., & Nasab, B. R. (2016). Carbon capture and storage (CCS) and its impacts on climate change and global warming. *J. Pet. Environ. Biotechnol*, *7*(9).

[158] Shaw, R., & Mukherjee, S. (2022). The development of carbon capture and storage (CCS) in India: A critical review. *Carbon Capture Science & Technology*, *2*, 100036.

[159] Shortall, R., Davidsdottir, B., & Axelsson, G. (2015). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and sustainable energy reviews*, *44*, 391-406.

[160] Shrestha, N., Chilkoor, G., Wilder, J., Gadhamshetty, V., & Stone, J. J. (2017). Potential water resource impacts of hydraulic fracturing from unconventional oil production in the Bakken shale. *Water Research*, *108*, 1-24.

[161] Soeder, D. J., & Soeder, D. J. (2021). Impacts to human health and ecosystems. *Fracking and the Environment: A scientific assessment of the environmental risks from hydraulic fracturing and fossil fuels*, 135-153.

[162] Soga, K., Alonso, E., Yerro, A., Kumar, K., & Bandara, S. (2016). Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method. *Géotechnique*, *66*(3), 248-273.

[163] Soltani, M., Kashkooli, F. M., Souri, M., Rafiei, B., Jabarifar, M., Gharali, K., & Nathwani, J. S. (2021). Environmental, economic, and social impacts of geothermal energy systems. *Renewable and Sustainable Energy Reviews*, *140*, 110750.

[164] Sowiżdżał, A., Starczewska, M., & Papiernik, B. (2022). Future technology mix—enhanced geothermal system (EGS) and carbon capture, utilization, and storage (CCUS)—an overview of selected projects as an example for future investments in Poland. *Energies*, *15*(10), 3505.

[165] Spada, M., Sutra, E., & Burgherr, P. (2021). Comparative accident risk assessment with focus on deep geothermal energy systems in the Organization for Economic Co-operation and Development (OECD) countries. *Geothermics*, *95*, 102142.

[166] Stober, I., & Bucher, K. (2013). Geothermal energy. *Germany: Springer-Verlag Berlin Heidelberg. doi*, *10*, 978-3.

[167] Sule, I., Imtiaz, S., Khan, F., & Butt, S. (2019). Risk analysis of well blowout scenarios during managed pressure drilling operation. *Journal of Petroleum Science and Engineering*, *182*, 106296.

[168] Suvin, P. S., Gupta, P., Horng, J. H., & Kailas, S. V. (2021). Evaluation of a comprehensive non-toxic, biodegradable and sustainable cutting fluid developed from coconut oil. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *235*(9), 1842-1850.

[169] Suzuki, A., Fukui, K. I., Onodera, S., Ishizaki, J., & Hashida, T. (2022). Data-driven geothermal reservoir modeling: Estimating permeability distributions by machine learning. *Geosciences*, *12*(3), 130.

[170] Szulecki, K., & Westphal, K. (2014). The cardinal sins of European energy policy: Nongovernance in an uncertain global landscape. *Global Policy*, *5*, 38-51.

[171] Tabatabaei, M., Kazemzadeh, F., Sabah, M., & Wood, D. A. (2022). Sustainability in natural gas reservoir drilling: A review on environmentally and economically friendly fluids and optimal waste management. *Sustainable Natural Gas Reservoir and Production Engineering*, 269-304.

[172] Tahmasebi, P., Kamrava, S., Bai, T., & Sahimi, M. (2020). Machine learning in geo-and environmental sciences: From small to large scale. *Advances in Water Resources*, *142*, 103619.

[173] Tapia, J. F. D., Lee, J. Y., Ooi, R. E., Foo, D. C., & Tan, R. R. (2016). Optimal CO2 allocation and scheduling in enhanced oil recovery (EOR) operations. *Applied energy*, *184*, 337-345.

[174] Teodoriu, C., & Bello, O. (2021). An outlook of drilling technologies and innovations: Present status and future trends. *Energies*, *14*(15), 4499.

[175] Tester, J. W., Beckers, K. F., Hawkins, A. J., & Lukawski, M. Z. (2021). The evolving role of geothermal energy for decarbonizing the United States. *Energy & environmental science*, *14*(12), 6211-6241.

[176] Thomas, L., Tang, H., Kalyon, D. M., Aktas, S., Arthur, J. D., Blotevogel, J., ... & Young, M. H. (2019). Toward better hydraulic fracturing fluids and their application in energy production: A review of sustainable technologies and reduction of potential environmental impacts. *Journal of Petroleum Science and Engineering*, *173*, 793-803.

[177] Tula, O. A., Adekoya, O. O., Isong, D., Daudu, C. D., Adefemi, A., & Okoli, C. E. (2004). Corporate advising strategies: A comprehensive review for aligning petroleum engineering with climate goals and CSR commitments in the United States and Africa. *Corporate Sustainable Management Journal, 2*(1), 32-38.

[178] Udegbunam, J. E. (2015). Improved well design with risk and uncertainty analysis.

[179] Ugwu, G. Z. (2015). An overview of pore pressure prediction using seismicallyderived velocities. *Journal of Geology and Mining Research*, *7*(4), 31-40.

[180] Van Oort, E., Chen, D., Ashok, P., & Fallah, A. (2021, March). Constructing deep closed-loop geothermal wells for globally scalable energy production by leveraging oil and gas ERD and HPHT well construction expertise. In *SPE/IADC Drilling Conference and Exhibition* (p. D021S002R001). SPE.

[181] Vesselinov, V. V., O'Malley, D., Frash, L. P., Ahmmed, B., Rupe, A. T., Karra, S., ... & Scharer, J. (2021). *Geo Thermal Cloud: Cloud Fusion of Big Data and Multi-Physics Models Using Machine Learning for Discovery, Exploration, and Development of Hidden Geothermal Resources* (No. LA-UR-21-24325). Los Alamos National Laboratory (LANL), Los Alamos, NM (United States).

[182] Vielma, W. E., & Mosti, I. (2014, November). Dynamic Modelling for Well Design, Increasing Operational Margins in Challenging Fields. In *Abu Dhabi International Petroleum Exhibition and Conference* (p. D041S071R003). SPE.

[183] Wang, K., Yuan, B., Ji, G., & Wu, X. (2018). A comprehensive review of geothermal energy extraction and utilization in oilfields. *Journal of Petroleum Science and Engineering*, *168*, 465-477.

[184] Waswa, A. M., Kedi,. W. E.., & Sula, N. (2015). Design and Implementation of a GSM based Fuel Leakage Monitoring System on Trucks in Transit. *Abstract of Emerging Trends in Scientific Research*, *3*, 1-18.

[185] Weldeslassie, T., Naz, H., Singh, B., & Oves, M. (2018). Chemical contaminants for soil, air and aquatic ecosystem. *Modern age environmental problems and their remediation*, 1-22.

[186] Wennersten, R., Sun, Q., & Li, H. (2015). The future potential for Carbon Capture and Storage in climate change mitigation–an overview from perspectives of technology, economy and risk. *Journal of cleaner production*, *103*, 724-736.

[187] Wilberforce, T., Baroutaji, A., El Hassan, Z., Thompson, J., Soudan, B., & Olabi, A. G. (2019). Prospects and challenges of concentrated solar photovoltaics and enhanced geothermal energy technologies. *Science of The Total Environment*, *659*, 851-861.

[188] Wojtanowicz, A. K. (2016). Environmental control of drilling fluids and produced water. *Environmental technology in the oil industry*, 101-165.

[189] Wu, Y., Wu, Y., Guerrero, J. M., & Vasquez, J. C. (2021). A comprehensive overview of framework for developing sustainable energy internet: From things-based energy network to services-based management system. *Renewable and Sustainable Energy Reviews*, *150*, 111409.

[190] Younger, P. L. (2015). Geothermal energy: Delivering on the global potential. *Energies*, *8*(10), 11737-11754.

[191] Yu, H., Chen, G., & Gu, H. (2020). A machine learning methodology for multivariate pore-pressure prediction. *Computers & Geosciences*, *143*, 104548.

[192] Yudha, S. W., Tjahjono, B., & Longhurst, P. (2022). Sustainable transition from fossil fuel to geothermal energy: A multi-level perspective approach. *Energies*, *15*(19), 7435.

[193] Zabbey, N., & Olsson, G. (2017). Conflicts–oil exploration and water. *Global challenges*, *1*(5), 1600015.

[194] Zhang, P., Ozowe, W., Russell, R. T., & Sharma, M. M. (2021). Characterization of an electrically conductive proppant for fracture diagnostics. *Geophysics*, *86*(1), E13-E20.

[195] Zhang, Z., & Huisingh, D. (2017). Carbon dioxide storage schemes: technology, assessment and deployment. *journal of cleaner production*, *142*, 1055-1064.

[196] Zhao, X., Li, D., Zhu, H., Ma, J., & An, Y. (2022). Advanced developments in environmentally friendly lubricants for water-based drilling fluid: a review. *RSC advances*, *12*(35), 22853-22868.