World Journal of
Advanced Science and Technology

Journal homepage: https://zealjournals.com/wjast/

ISSN: 2945-3178 (Online)

(REVIEW ARTICLE)

Check for updates

Circular economy models for sustainable resource management in energy supply chains

Ekene Cynthia Onukwulu [1, *], Mercy Odochi Agho [2] and Nsisong Louis Eyo-Udo [3]

[1] *Total Energies Nigeria Ltd.*
[2] *Independent Researcher, Portharcourt Nigeria.*
[3] *Independent Researcher, Lagos Nigeria.*

World Journal of Advanced Science and Technology, 2022, 02(02), 034-057

Publication history: Received on 10 October 2022; revised on 22 November 2022; accepted on 25 November 2022

Article DOI: https://doi.org/10.53346/wjast.2022.2.2.0048

Abstract

The transition to a circular economy offers a promising approach to sustainable resource management in energy supply chains, particularly within the context of reducing environmental impacts and enhancing resource efficiency. A circular economy model focuses on minimizing waste, maximizing resource utilization, and promoting the reuse, recycling, and remanufacturing of materials. This paper explores the application of circular economy principles in energy supply chains, highlighting their potential to transform traditional linear supply chains into more sustainable, closed-loop systems. In the energy sector, the circular economy can be implemented through various practices such as extending the lifecycle of energy infrastructure, reducing carbon emissions, and optimizing resource extraction and consumption. Key strategies include the recycling of energy materials (such as metals and plastics), repurposing equipment and infrastructure, and promoting energy efficiency across the entire supply chain. Moreover, the role of renewable energy systems, such as solar, wind, and bioenergy, is crucial in supporting circular economy models by offering sustainable alternatives to fossil fuels and enabling the reduction of environmental footprints. The paper also addresses the importance of designing energy products and services with circularity in mind, ensuring that materials and components can be recovered and reused after their useful life. Technological innovation, particularly in digitalization and artificial intelligence, plays a critical role in optimizing the management of resources in circular supply chains. Through data analytics and predictive modeling, energy companies can better track and manage material flows, ensuring higher efficiency and reduced waste. Additionally, collaboration among stakeholders, including suppliers, governments, and consumers, is vital for fostering circularity in energy supply chains. By implementing circular economy models, energy companies can not only enhance sustainability but also realize cost savings, improve resilience, and meet regulatory compliance. This paper concludes with recommendations for the energy sector to accelerate the adoption of circular economy practices, ensuring a sustainable and resource-efficient future.

Keywords: Circular Economy; Sustainable Resource Management; Energy Supply Chains; Recycling; Renewable Energy; Energy Efficiency; Digitalization; Waste Reduction; Lifecycle Extension.

1 Introduction

The circular economy is a model of production and consumption that emphasizes reducing waste, reusing resources, and recycling materials to create a closed-loop system. Unlike the traditional linear economy, which follows a "take, make, dispose" approach, the circular economy focuses on maintaining the value of products, materials, and resources in the economy for as long as possible (Adejugbe & Adejugbe, 2014, Bassey, 2022, Okeke, et al., 2022, Dickson & Fanelli, 2018). This approach is crucial for sustainable resource management, especially in sectors such as energy, where resource depletion and environmental impact are growing concerns.

* Corresponding author: Ekene Cynthia Onukwulu

Copyright © 2022 Author(s) retain the copyright of this article. This article is published under the terms of the Creative Commons Attribution Liscense 4.0.

The energy sector faces significant environmental challenges, including high levels of resource consumption, waste generation, and carbon emissions. Conventional energy production methods, such as fossil fuel extraction and combustion, are not only unsustainable but also contribute to climate change, air pollution, and environmental degradation. Additionally, energy supply chains are often marked by inefficiencies, from the extraction of raw materials to the distribution of energy to consumers (Agupugo, et al., 2022, da Silva Veras, et al., 2017, Dominy, et al., 2018, Napp, et al., 2014). These inefficiencies lead to the depletion of natural resources and increased environmental pressure, necessitating a shift toward more sustainable practices.

This paper explores the role of circular economy models in transforming energy supply chains, aiming to provide a comprehensive understanding of how adopting circular principles can reduce resource consumption, enhance efficiency, and mitigate environmental impact. By examining the potential for circular economy practices in areas such as renewable energy integration, waste-to-energy technologies, and energy efficiency measures, this paper seeks to contribute to the growing body of knowledge on sustainable energy management. The scope of this paper includes a discussion on the various strategies for implementing circular economy models in the energy sector and the potential benefits these approaches offer for both environmental sustainability and economic resilience (Adeniran, et al., 2022, Okeke, et al., 2022, Dong, et al., 2019, Lindi, 2017).

2 Understanding Circular Economy Principles

The concept of a circular economy is gaining increasing importance as the world grapples with the challenges of resource depletion, environmental degradation, and climate change. The circular economy model focuses on minimizing waste and maximizing the use of resources, promoting sustainability and reducing environmental impact. Central to the concept of a circular economy are four core principles: reduce, reuse, recycle, and remanufacture. These principles offer a fundamental shift from the traditional linear economy, which has been the dominant model for industrial production and consumption. Understanding these principles and their application in energy supply chains is essential for developing sustainable practices that can address the inefficiencies and environmental issues inherent in the sector.

The first core principle of circular economy is "reduce." This principle advocates for the minimization of resource use and waste generation throughout the production and consumption processes. In the context of energy supply chains, reducing the consumption of raw materials, such as fossil fuels, can have significant environmental benefits. The extraction and burning of fossil fuels are among the primary contributors to greenhouse gas emissions, air pollution, and environmental degradation (Okoroafor, et al., 2022, Okwiri, 2017, Olayiwola & Sanuade, 2021, Shahbaz, et al., 2017). By reducing the dependence on these non-renewable resources, energy companies can help curb the negative impacts of energy production on the environment. This reduction can also extend to energy consumption, where more efficient systems and technologies can be employed to minimize energy waste across supply chains. For example, energy-efficient technologies, such as smart grids and demand response systems, can help optimize energy distribution and reduce unnecessary consumption.

The second principle of circular economy is "reuse," which emphasizes the importance of finding new uses for products or materials that have reached the end of their initial life cycle. Reusing materials and components within energy supply chains can significantly extend their life and reduce the need for new resources. For instance, in the renewable energy sector, components such as solar panels, wind turbines, and batteries can be refurbished and reused after their initial lifespan. Rather than discarding these materials, they can be reintroduced into the production process, reducing the need for raw material extraction and minimizing waste. Reuse can also be applied to energy systems, such as repurposing energy storage devices or finding secondary uses for byproducts of energy generation (Akpan, 2019, Bassey, 2022, Oyeniran, et al., 2022, Dufour, 2018, Martin, 2022). By prioritizing reuse, energy companies can lower costs and reduce their environmental footprint.

"Recycle" is the third core principle of circular economy, and it is closely related to the previous two principles. Recycling involves processing used materials into new products, preventing them from being discarded as waste. In energy supply chains, recycling can take many forms, such as the recovery of valuable metals from decommissioned wind turbines or the recycling of batteries used in energy storage systems. This reduces the need for new raw materials, which are often scarce or environmentally damaging to extract. Recycling also helps to divert waste from landfills and reduces pollution (Aftab, et al., 2017, Okeke, et al., 2022, El Bilali, et al., 2022, McCollum, et al., 2018). One key area where recycling has gained attention in the energy sector is in the management of electronic waste (e-waste). Solar panels, batteries, and other energy-related technologies often contain materials such as silicon, lithium, and cobalt, which are valuable and can be recycled for use in new products. As the demand for renewable energy sources grows, so too does the need for effective recycling systems to manage the materials used in these technologies.

The fourth core principle of circular economy is "remanufacture," which refers to the process of restoring used products to a like-new condition by repairing, upgrading, or replacing worn-out components. In energy supply chains, remanufacturing can help extend the life of expensive equipment and reduce the need for new production. For example, remanufacturing turbine blades for wind energy or refurbishing power plants can reduce the environmental and economic costs of building new infrastructure (Kabeyi & Olanrewaju, 2022, Kinik, Gumus & Osayande, 2015, Lohne, et al., 2016). Remanufacturing is not limited to the repair of physical components; it can also apply to the revitalization of energy systems. For instance, in the power generation sector, outdated or inefficient power plants can be upgraded with new technologies to enhance their performance and reduce their environmental impact. By incorporating remanufacturing into energy supply chains, companies can conserve resources, reduce waste, and support the transition to a more sustainable energy infrastructure.

Comparing the principles of circular economy with the traditional linear economy model highlights the fundamental differences between these two approaches, especially in the energy sector. The traditional linear economy is based on a "take, make, dispose" model, where resources are extracted, used to create products, and then discarded after use (Sule, et al., 2019, Vesselinov, et al., 2021, Wennersten, Sun & Li, 2015, Zhang & Huisingh, 2017). This model relies heavily on the continuous availability of cheap, abundant raw materials and has resulted in significant inefficiencies, waste, and environmental degradation. In the energy sector, the linear economy has led to the over-exploitation of fossil fuels, a reliance on polluting technologies, and a lack of consideration for the long-term environmental consequences of energy production. The linear economy has contributed to the depletion of non-renewable resources, increasing carbon emissions, and environmental damage, making it unsustainable in the face of rising global energy demand and environmental challenges.

In contrast, the circular economy model focuses on closing the loop, promoting the efficient use of resources, and reducing waste at every stage of the energy supply chain. By shifting from the linear "take, make, dispose" mindset to the circular "reduce, reuse, recycle, remanufacture" approach, the energy sector can address many of the challenges associated with resource inefficiencies and environmental harm (Adejugbe, 2020, Beiranvand & Rajaee, 2022, Okeke, et al., 2022, Oyeniran, et al., 2022). The adoption of circular economy principles allows for a more sustainable and resilient energy system that prioritizes resource conservation, reduces dependence on finite resources, and mitigates the environmental impacts of energy production and consumption.

The benefits of adopting circular economy practices in energy supply chains are numerous and can have a transformative impact on both the environment and the economy. One of the most significant benefits is the reduction of environmental impacts. By prioritizing the reduction of resource consumption, reusing materials, recycling waste, and remanufacturing products, the energy sector can decrease its carbon footprint, lower pollution levels, and reduce the depletion of natural resources (Adenugba & Dagunduro, 2021, Popo-Olaniyan, et al., 2022, Eldardiry & Habib, 2018, Zhao, et al., 2022). This contributes to the broader goal of addressing climate change and achieving global sustainability targets. Circular economy practices also promote greater resource efficiency, which can help energy companies lower operational costs and improve their bottom lines. For example, by reusing materials or remanufacturing equipment, energy companies can reduce the need for costly raw material extraction and new production, leading to significant cost savings over time.

Furthermore, circular economy principles encourage innovation within the energy sector. The need to rethink resource use and waste management drives the development of new technologies and business models that are more sustainable and efficient. For instance, advancements in renewable energy technologies, energy storage systems, and smart grids are all part of the circular economy transition (Olufemi, Ozowe & Komolafe, 2011, Ozowe, 2018, Pan, et al., 2019, Shahbazi & Nasab, 2016). By embracing circular economy practices, energy companies can position themselves as leaders in sustainability, enhancing their reputations and attracting environmentally-conscious consumers and investors. This can also lead to new market opportunities, as demand for sustainable energy solutions continues to rise.

In conclusion, the core principles of circular economy—reduce, reuse, recycle, and remanufacture—offer a comprehensive framework for transforming energy supply chains into more sustainable, resource-efficient systems. By adopting these principles, the energy sector can mitigate environmental impacts, enhance operational efficiency, and foster innovation. The shift from a traditional linear economy to a circular economy model is essential for creating a more sustainable and resilient energy infrastructure that can meet the challenges of the future.

3 Application of Circular Economy in Energy Supply Chains

The application of circular economy principles in energy supply chains presents a transformative approach to sustainable resource management. Circular economy models focus on reducing waste, improving resource efficiency, and creating closed-loop systems where resources are reused, recycled, and remanufactured. In the context of energy supply chains, these principles aim to optimize resource use, reduce environmental impact, and enhance the sustainability of energy systems. By applying circular economy strategies, the energy sector can address the inefficiencies and environmental challenges inherent in traditional linear models, contributing to the transition to a more sustainable and resilient energy future.

Resource efficiency and waste minimization are key objectives of the circular economy in energy supply chains. The traditional linear economy is characterized by a "take, make, dispose" approach, where resources are extracted, used, and discarded, often with significant environmental consequences (Adejugbe & Adejugbe, 2018, Bello, et al., 2022, Okeke, et al., 2022, Popo-Olaniyan, et al., 2022). In contrast, the circular economy focuses on reducing the consumption of resources and minimizing waste at every stage of the supply chain. In the energy sector, this begins with the extraction of raw materials, which are often non-renewable and environmentally damaging. Circular economy principles encourage the use of renewable and recycled materials, as well as the reduction of raw material consumption through more efficient processes.

Strategies for reducing resource consumption across the energy supply chain include optimizing energy production processes, increasing energy efficiency, and transitioning to renewable energy sources. Energy efficiency improvements, such as upgrading power plants with more advanced technology, can significantly reduce the amount of energy needed to produce electricity. Furthermore, optimizing energy transmission and distribution networks can minimize energy losses and improve overall system efficiency (Abdelaal, Elkatatny & Abdulraheem, 2021, Epelle & Gerogiorgis, 2020, Misra, et al., 2022). Energy-efficient technologies, such as advanced metering infrastructure, smart grids, and demand-response systems, can also help manage energy consumption more effectively, reducing the need for additional energy production. The adoption of renewable energy sources, such as wind, solar, and hydropower, also supports resource efficiency by reducing reliance on finite fossil fuels and lowering the carbon footprint of energy production.

Waste reduction techniques in energy supply chains are another crucial aspect of circular economy application. Repurposing, recycling, and reusing energy infrastructure and materials can help minimize waste and reduce the demand for new resources. For example, in the renewable energy sector, the lifecycle of energy infrastructure, such as wind turbines and solar panels, can be extended through effective recycling and repurposing (Khalid, et al., 2016, Kiran, et al., 2017, Li, et al., 2019, Marhoon, 2020, Nimana, Canter & Kumar, 2015). Wind turbine blades, which are typically made from composite materials, can be difficult to recycle, but new technologies are emerging that can help recover valuable materials from decommissioned turbines, such as fiberglass and metals. Similarly, solar panels, which have a lifespan of 20-30 years, can be recycled to recover materials like silicon, silver, and copper, which can be reused in the production of new panels. This not only reduces the need for new raw materials but also prevents harmful waste from entering landfills, contributing to a more sustainable energy system.

Circular design principles play an important role in making energy products more sustainable over their entire lifecycle. Designing products for longer lifecycles and recyclability is a fundamental strategy for reducing waste and improving resource efficiency. In the energy sector, this can be applied to various types of infrastructure and equipment, from power plants and transmission lines to renewable energy technologies such as wind turbines, solar panels, and energy storage systems (AlBahrani, et al., 2022, Cordes, et al., 2016, Ericson, Engel-Cox & Arent, 2019, Zabbey & Olsson, 2017). Circular design encourages the use of durable materials, modular components, and systems that can be easily disassembled and reused or recycled. For example, in wind turbine design, components such as blades, nacelles, and towers can be designed with recyclability in mind, allowing them to be more easily broken down and repurposed at the end of their useful life.

Examples of circular design principles in energy equipment and infrastructure are becoming more prevalent as the demand for sustainable energy solutions grows. One such example is the development of recyclable solar panels, which are designed to be more easily disassembled and recycled at the end of their operational life. Companies are also exploring ways to improve the recyclability of wind turbine blades, which are traditionally challenging to process due to their composite materials (Suvin, et al., 2021, Van Oort,et al., 2021, Wilberforce, et al., 2019, Yudha, Tjahjono & Longhurst, 2022). Innovative design approaches, such as creating wind turbine blades using recyclable thermoplastic resins, are helping to address these challenges and reduce the environmental impact of decommissioned turbines. Additionally, the design of energy storage systems, such as batteries, is evolving to focus on increasing the lifespan of the batteries and improving their recyclability. Lithium-ion batteries, commonly used in energy storage, are being designed with more sustainable materials and better recycling capabilities to minimize waste and reduce the environmental footprint of battery production.

Extending the operational life of energy systems and components is another critical aspect of circular economy applications in the energy sector. Energy infrastructure, such as power plants, transmission lines, and renewable energy systems, often represents a significant investment, and extending their lifespan can provide both economic and environmental benefits. One way to achieve this is through maintenance, refurbishment, and upgrading of energy infrastructure to support circularity (Ozowe, Zheng & Sharma, 2020, Pereira, et al., 2022, Seyedmohammadi, 2017, Stober & Bucher, 2013). Maintenance and refurbishment can help prevent premature failure and extend the operational life of equipment, reducing the need for costly replacements and minimizing waste. In power plants, regular maintenance and upgrades can improve efficiency, reduce emissions, and increase the lifespan of critical equipment such as turbines and boilers. Refurbishing aging infrastructure, rather than decommissioning it, can be a more cost-effective and environmentally friendly approach, particularly in the case of large-scale energy systems that require significant capital investment.

In the renewable energy sector, extending the operational life of energy systems can be achieved through regular maintenance, retrofitting, and upgrading of renewable energy technologies. For example, wind turbines can be refurbished to improve their efficiency, or their components can be replaced with newer, more efficient parts to extend their operational life. Solar panels, too, can benefit from maintenance and upgrades that increase their performance and longevity (Adejugbe & Adejugbe, 2015, Okeke, et al., 2022, Erofeev, et al., 2019, Mohsen & Fereshteh, 2017). By extending the lifespan of renewable energy infrastructure, energy companies can reduce the need for new installations, minimizing resource consumption and waste generation.

Energy infrastructure lifespan extension is also supported by digital technologies, such as predictive maintenance and condition monitoring. These technologies enable energy companies to monitor the performance of their systems in real-time and identify potential issues before they lead to failure. By using data analytics and machine learning algorithms, companies can optimize maintenance schedules, improve system reliability, and reduce the risk of costly repairs or replacements (Ahlstrom, et al., 2020, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Najibi, et al., 2017). Predictive maintenance not only extends the life of energy infrastructure but also enhances operational efficiency and reduces downtime, contributing to the overall sustainability of energy supply chains.

In conclusion, the application of circular economy principles in energy supply chains offers significant opportunities for improving resource efficiency, minimizing waste, and extending the life of energy infrastructure. Strategies such as reducing resource consumption, repurposing, recycling, and reusing materials, and designing for circularity can help create a more sustainable and resilient energy system. By embracing circular economy practices, energy companies can reduce their environmental impact, lower costs, and improve the efficiency and reliability of energy production and distribution. As the demand for sustainable energy solutions continues to grow, the adoption of circular economy principles in the energy sector will play a critical role in shaping a more sustainable and circular future for the industry.

4 Renewable Energy and Circular Economy Integration

The integration of renewable energy with circular economy models offers a powerful approach to achieving sustainable resource management in energy supply chains. As the world moves toward a more sustainable future, there is growing recognition of the need to transition from linear to circular economic models, where the focus is on reducing, reusing, and recycling resources. Renewable energy sources, such as solar, wind, and bioenergy, are central to this transformation. By combining the principles of circular economy with renewable energy, it is possible to create systems that not only generate clean energy but also minimize waste, maximize resource efficiency, and reduce environmental impact across the entire energy supply chain.

Renewable energy plays a critical role in circular economy models by providing a sustainable alternative to traditional fossil fuel-based energy systems. Solar, wind, and bioenergy are abundant, clean, and renewable resources that can be harnessed to meet growing global energy demands without depleting finite natural resources or generating harmful emissions. The role of renewable energy in circular economy models is multifaceted (Abdelfattah, et al., 2021, Craddock, 2018, Eshiet & Sheng, 2018, Martin-Roberts, et al., 2021). First and foremost, it helps reduce dependence on fossil fuels, which are non-renewable and contribute significantly to environmental degradation. Fossil fuel extraction and use are associated with high levels of carbon emissions, air pollution, and habitat destruction, making the shift to renewable energy sources a key element in reducing the ecological footprint of the energy sector.

In the context of a circular economy, renewable energy sources contribute to sustainability and resource management in several ways. One of the core principles of the circular economy is resource efficiency, which involves minimizing the consumption of raw materials and reducing waste throughout the lifecycle of products and systems (Olufemi, Ozowe & Afolabi, 2012, Ozowe, 2021, Quintanilla, et al., 2021, Shortall, Davidsdottir & Axelsson, 2015). Renewable energy systems, particularly those based on solar and wind, offer highly efficient and low-waste alternatives to traditional energy production. Unlike fossil fuels, which require extensive extraction processes, renewable energy sources like sunlight and wind are abundant and available locally, eliminating the need for resource-intensive extraction and transportation. Additionally, renewable energy systems, such as solar panels and wind turbines, have much lower environmental impacts during operation, with no direct emissions or waste byproducts.

The integration of renewable energy into circular economy models also enables more sustainable energy production through closed-loop systems. For example, solar panels and wind turbines are designed to be durable and long-lasting, and at the end of their operational life, they can be recycled or repurposed to recover valuable materials, such as silicon, aluminum, and rare earth metals. This process of reusing materials from renewable energy infrastructure contributes to reducing the demand for new raw materials, further minimizing environmental impact and conserving resources (Jomthanachai, Wong & Lim, 2021, Li, et al., 2022, Luo, et al., 2019, Mosca, et al., 2018). The circular approach to renewable energy production and use also supports the concept of energy independence, as local renewable resources can be harnessed to generate energy, reducing reliance on imported fossil fuels and enhancing energy security.

Renewable energy also plays a crucial role in resource management within the circular economy by enabling more sustainable approaches to waste management. Bioenergy, for example, is derived from organic waste materials, such as agricultural residues, food waste, and forestry byproducts. By converting waste into energy, bioenergy systems help reduce landfill waste, lower greenhouse gas emissions, and create valuable resources from otherwise discarded materials (Agupugo, et al., 2022, Dagunduro & Adenugba, 2020, Okeke, et al., 2022, Nduagu & Gates, 2015). Bioenergy is a prime example of how renewable energy can be integrated into circular economy models to close the loop between waste production and energy consumption, turning what would be waste into a source of sustainable power.

The synergies between circular economy and renewable energy are particularly evident in the way these two concepts work together to reduce dependence on fossil fuels. One of the main goals of the circular economy is to minimize the extraction of new resources, reduce waste, and close material loops, and renewable energy sources contribute significantly to these objectives by providing clean and sustainable energy solutions. For instance, the integration of renewable energy into manufacturing processes and supply chains can help reduce the need for fossil fuels in production, transportation, and storage, resulting in lower carbon emissions and reduced environmental impacts (Adeniran, et al., 2022, Efunniyi, et al., 2022, Eyinla, et al., 2021, Mrdjen & Lee, 2016). Renewable energy systems, such as solar panels and wind turbines, have the potential to power the entire lifecycle of energy infrastructure, from production to end-of-life recycling, without relying on fossil fuels at any stage.

In addition to reducing dependence on fossil fuels, the combination of renewable energy and circular economy principles offers significant opportunities for enhancing energy efficiency and optimizing resource use across energy supply chains. The use of renewable energy in manufacturing processes, for example, can reduce the carbon footprint of production while enabling greater resource efficiency (Suzuki, et al., 2022, Ugwu, 2015, Vielma & Mosti, 2014, Wojtanowicz, 2016, Zhang, et al., 2021). In the case of solar panel production, much of the energy-intensive manufacturing process can be powered by renewable energy, thereby reducing the overall environmental impact of panel production. Moreover, as the cost of renewable energy continues to decline, it becomes increasingly economically viable to integrate renewable energy into industrial processes, creating a feedback loop that drives further demand for clean energy solutions.

The adoption of renewable energy in circular economy models also supports the shift toward decentralized energy systems, where power generation and distribution are more localized. This approach reduces the need for extensive energy transmission infrastructure, minimizing energy losses and improving the efficiency of the entire energy supply chain. By generating energy closer to where it is needed, decentralized renewable energy systems can reduce transportation costs, lower grid congestion, and increase the resilience of local energy systems (Adenugba & Dagunduro, 2019, Elujide, et al., 2021, Okeke, et al., 2022, Njuguna, et al., 2022). This decentralization also allows communities and businesses to become more self-sufficient, providing greater control over their energy use and reducing reliance on centralized fossil fuel-based energy sources.

Furthermore, renewable energy technologies themselves are evolving to become more circular in design. Advances in energy storage technologies, such as lithium-ion batteries and other energy storage solutions, are helping to improve the efficiency and reliability of renewable energy systems by storing excess energy generated during peak production times for use during periods of low demand (Adejugbe & Adejugbe, 2020, Elujide, et al., 2021, Fakhari, 2022, Mikunda, et al., 2021). This energy storage capability enables renewable energy to be used more consistently and helps balance the intermittent nature of some renewable sources, such as wind and solar. Additionally, research into second-life applications for batteries is providing new opportunities to reuse and repurpose batteries from electric vehicles and other energy storage systems, extending their useful life and reducing waste.

The synergy between renewable energy and circular economy models also extends to the development of smart grids and energy management systems. Smart grids use digital technologies and data analytics to optimize energy distribution, reduce waste, and enhance the integration of renewable energy into the grid (Ozowe, et al., 2020, Radwan, 2022, Salam & Salam, 2020, Shaw & Mukherjee, 2022). By allowing for real-time monitoring and management of energy consumption, smart grids can help improve the efficiency of energy supply chains, reduce energy losses, and enable more effective integration of decentralized renewable energy sources. Additionally, energy management systems can optimize the use of renewable energy in industrial and commercial applications, ensuring that energy is used as efficiently as possible and minimizing waste.

The integration of renewable energy and circular economy models in energy supply chains offers significant potential for reducing the environmental impact of energy systems while simultaneously enhancing resource efficiency, sustainability, and resilience. By harnessing renewable energy sources such as solar, wind, and bioenergy, and applying circular economy principles to energy production, consumption, and waste management, it is possible to create a more sustainable and circular energy system. As renewable energy technologies continue to evolve and costs decline, the opportunities for integrating these technologies into circular economy models will only increase, providing a pathway to a cleaner, more sustainable energy future that benefits both the environment and society.

5 Technological Innovations Enabling Circularity in Energy Supply Chains

Technological innovations are essential in enabling circularity within energy supply chains, as they facilitate the seamless implementation of circular economy principles such as resource optimization, waste minimization, and lifecycle management. The rapid advancement of digital technologies, including big data analytics, artificial intelligence (AI), and the Internet of Things (IoT), has brought transformative capabilities to energy supply chains, making them more efficient, resilient, and sustainable. These technologies play a crucial role in optimizing resource flows, improving energy efficiency, and ensuring the effective recycling and reuse of materials within the circular economy framework. Furthermore, predictive modeling and material tracking systems enhance lifecycle management and promote responsible end-of-life disposal, contributing to a closed-loop system in energy production and consumption.

Digital technologies are at the forefront of enabling circular economy practices in energy supply chains. Big data analytics has emerged as a powerful tool for analyzing and optimizing complex systems (Ahmad, et al., 2022, Waswa, Kedi & Sula, 2015, Farajzadeh, et al., 2022, Najibi & Asef, 2014). By collecting and processing large volumes of data from energy generation, distribution, and consumption processes, big data analytics enables energy providers to identify inefficiencies, predict demand patterns, and optimize resource allocation. For example, big data can monitor energy usage trends in real time, helping companies make data-driven decisions to reduce waste and improve efficiency. In renewable energy systems, such as solar and wind, big data analytics can be used to forecast energy production based on weather conditions, ensuring that energy is stored or distributed effectively to minimize losses and maximize utilization.

Artificial intelligence (AI) further enhances the potential of big data by providing advanced analytical capabilities and enabling predictive modeling. AI algorithms can identify patterns and correlations within vast datasets, offering insights that would be impossible to discern manually. In the context of energy supply chains, AI can optimize operations by predicting equipment failures, identifying maintenance needs, and suggesting energy-saving measures. For example, AI-driven predictive maintenance systems can monitor the performance of wind turbines or solar panels, detecting anomalies before they lead to system failures (Ali, et al., 2022, Beiranvand & Rajaee, 2022, Farajzadeh, et al., 2022, Mushtaq, et al., 2020). By extending the operational lifespan of energy infrastructure and minimizing downtime, AI contributes to the circular economy goal of maximizing resource efficiency and reducing waste.

The Internet of Things (IoT) serves as a foundational technology for collecting and transmitting data across energy supply chains. IoT devices, such as sensors and smart meters, enable real-time monitoring of energy systems, providing detailed insights into energy usage, resource consumption, and waste generation. These devices play a critical role in implementing circular economy principles by tracking the flow of materials and energy throughout the supply chain. For instance, IoT sensors can monitor the condition of energy equipment, ensuring that maintenance is carried out only when necessary, thereby avoiding unnecessary repairs and resource wastage (Kabeyi, 2019, Kumari & Ranjith, 2019, Li

& Zhang, 2018, Mac Kinnon, Brouwer & Samuelsen, 2018). Additionally, IoT-enabled systems can automate energy management processes, such as adjusting energy usage in response to demand fluctuations, further enhancing efficiency and sustainability.

Predictive modeling is another key innovation that supports lifecycle management and waste reduction in energy supply chains. By using advanced algorithms and simulation techniques, predictive modeling allows energy providers to anticipate future scenarios and plan accordingly. For example, predictive models can estimate the degradation rate of energy equipment, such as batteries or solar panels, enabling companies to schedule maintenance and replacements proactively (Alagorni, Yaacob & Nour, 2015, Okeke, et al., 2022, Popo-Olaniyan, et al., 2022, Spada, Sutra & Burgherr, 2021). This approach not only reduces the risk of unexpected failures but also ensures that resources are used more efficiently over the lifespan of the equipment. Predictive modeling can also be applied to waste management, forecasting the volume and type of waste generated by energy systems and identifying opportunities for recycling or repurposing materials.

Technologies for tracking materials are vital for ensuring proper recycling and reuse within the circular economy framework. Blockchain, for example, offers a secure and transparent way to track materials across the energy supply chain. By recording every transaction and movement of materials on a decentralized ledger, blockchain ensures that all stakeholders have access to accurate and tamper-proof information. This level of transparency is essential for verifying the origin, composition, and destination of materials, making it easier to recycle and reuse them responsibly. For instance, blockchain can be used to track the lifecycle of batteries in electric vehicles, ensuring that they are properly recycled or repurposed at the end of their life. Similarly, it can monitor the supply chain of renewable energy components, such as wind turbine blades, to ensure that valuable materials are recovered and reintroduced into the production cycle.

Material tracking systems also play a critical role in promoting circularity by enabling the identification of materials with high recycling potential. Advanced sorting technologies, such as robotics and machine vision, are increasingly being used to separate and process materials in recycling facilities (Adejugbe & Adejugbe, 2016, Gil-Ozoudeh, et al., 2022, Garia, et al., 2019, Nguyen, et al., 2014). These technologies can identify different types of materials, such as metals, plastics, and composites, with high precision, ensuring that they are sorted correctly and recycled efficiently. In the energy sector, such systems can be used to recover valuable materials from decommissioned equipment, such as copper from electrical cables or rare earth metals from wind turbine magnets. By improving the efficiency of material recovery processes, these innovations contribute to reducing the environmental impact of energy systems and conserving natural resources.

The integration of digital technologies with circular economy models also enables more effective collaboration and information sharing among stakeholders in the energy supply chain. Digital platforms can facilitate communication and coordination between manufacturers, suppliers, recyclers, and consumers, ensuring that materials are managed responsibly throughout their lifecycle. For example, a digital platform can connect energy providers with recycling companies, streamlining the process of collecting and recycling end-of-life energy equipment. Additionally, such platforms can provide consumers with information on how to dispose of or recycle energy products, promoting greater participation in circular economy practices.

Another critical application of technology in enabling circularity is the development of innovative recycling and repurposing techniques. For example, advancements in chemical recycling have made it possible to break down complex materials, such as composite wind turbine blades, into their constituent components, which can then be reused in new products (Szulecki & Westphal, 2014, Thomas, et al., 2019, Udegbunam, 2015), Yu, Chen & Gu, 2020. Similarly, thermal and mechanical recycling methods are being used to recover valuable materials from photovoltaic panels and batteries. These technologies not only reduce the amount of waste sent to landfills but also create economic opportunities by recovering high-value materials that can be sold or reused in manufacturing.

In addition to recycling, technology also supports the reuse and refurbishment of energy infrastructure. For example, companies are increasingly using digital twin technology to create virtual replicas of energy systems, enabling them to simulate and test different scenarios for extending the lifespan of equipment. By identifying potential issues and optimizing maintenance schedules, digital twins can help energy providers maximize the operational life of their assets, reducing the need for new resources and minimizing waste. Refurbishment programs, supported by data from IoT devices and predictive models, can also extend the life of energy equipment, such as transformers or generators, by replacing worn-out components and restoring their performance.

In conclusion, technological innovations are driving the transition toward circularity in energy supply chains by enabling more efficient use of resources, reducing waste, and promoting sustainable practices. Digital technologies such as big data analytics, AI, and IoT provide the tools needed to optimize operations, track materials, and implement predictive maintenance. Predictive modeling and material tracking systems enhance lifecycle management and support responsible recycling and reuse. As these technologies continue to evolve, they will play an increasingly important role in achieving the goals of the circular economy, creating a more sustainable and resilient energy sector that benefits both the environment and society. By leveraging these innovations, energy providers can transform their supply chains into closed-loop systems that minimize resource consumption and environmental impact, paving the way for a sustainable energy future.

6 Collaboration and Stakeholder Engagement

Collaboration and stakeholder engagement are critical to the successful adoption and implementation of circular economy models for sustainable resource management in energy supply chains. Transitioning from traditional linear systems to circular frameworks requires the coordinated efforts of multiple stakeholders, including energy providers, suppliers, governments, policymakers, consumers, and civil society. Such collaboration ensures that circular economy principles are effectively integrated into the energy sector, fostering innovations in resource management, waste reduction, and sustainable energy practices. The importance of stakeholder collaboration is underscored by the complex nature of energy supply chains, which involve diverse actors and processes that span production, distribution, consumption, and end-of-life management.

The adoption of circular economy practices within the energy sector begins with the recognition that no single entity can achieve circularity independently. Stakeholders must work together to redesign supply chains, share resources, and co-create solutions that align with the principles of reducing, reusing, recycling, and remanufacturing. Collaboration fosters the exchange of knowledge, expertise, and technologies, enabling stakeholders to address common challenges such as resource inefficiencies, waste generation, and environmental degradation (Agemar, Weber & Schulz, 2014, Okeke, et al., 2022, Ghani, Khan & Garaniya, 2015, Sowiżdżał, Starczewska & Papiernik, 2022). For instance, partnerships between energy companies and suppliers can facilitate the development of energy systems designed for longer lifespans and easier recycling, while collaboration with governments can ensure that regulatory frameworks support circular practices.

Suppliers play a pivotal role in promoting circularity by adopting sustainable practices and providing materials that align with circular economy principles. Collaboration among suppliers and energy companies can lead to the sourcing of renewable and recyclable materials, reducing the environmental footprint of energy infrastructure. For example, the use of recycled metals in the production of wind turbines and solar panels demonstrates how supplier collaboration can drive resource efficiency. By working closely with their suppliers, energy companies can also establish closed-loop systems where end-of-life materials are collected, recycled, and reintroduced into the supply chain, minimizing waste and conserving resources.

Governments and policymakers are equally essential stakeholders in the transition to circular economy models. Their role involves creating policy frameworks and incentives that encourage circular practices across the energy sector. Regulatory measures, such as extended producer responsibility (EPR) programs, require energy companies to take accountability for the entire lifecycle of their products, including end-of-life management. Such policies incentivize companies to design products with recyclability and durability in mind, promoting circularity from the outset (Ozowe, Russell & Sharma, 2020, Rahman, Canter & Kumar, 2014, Rashid, Benhelal & Rafiq, 2020). Governments can also provide financial incentives, such as tax credits and subsidies, to support the adoption of circular technologies and practices. For instance, subsidies for renewable energy projects that incorporate circular design principles can accelerate the integration of circular economy models into energy supply chains.

Consumers are another critical stakeholder group whose engagement is vital for promoting circular economy practices. Public awareness and education campaigns can empower consumers to make informed choices that support circularity, such as prioritizing renewable energy options and participating in recycling programs. Collaboration between energy providers and consumers can also lead to the development of innovative solutions for energy use and waste management. For example, community-based renewable energy projects, where consumers collectively invest in and share renewable energy infrastructure, exemplify how collaboration can create sustainable and inclusive energy systems (Abdo, 2019, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Glassley, 2014, Soltani, et al., 2021). Additionally, consumers' willingness to adopt energy-efficient technologies, such as smart meters and energy storage systems, contributes to the broader goals of circular economy models.

The role of civil society and non-governmental organizations (NGOs) in promoting circular economy practices cannot be overlooked. These organizations act as intermediaries, facilitating dialogue and collaboration among stakeholders, advocating for sustainable policies, and holding companies accountable for their environmental impact. NGOs also play a key role in raising awareness about the benefits of circular economy models and driving consumer engagement. By collaborating with energy companies, civil society organizations can help implement community-based initiatives that promote resource efficiency and waste reduction.

Collaboration is particularly important in addressing the challenges associated with end-of-life management in the energy sector. Decommissioning energy infrastructure, such as wind turbines, solar panels, and batteries, generates significant amounts of waste that must be managed responsibly to avoid environmental harm (Agu, et al., 2022, Diao & Ghorbani, 2018, Gil-Ozoudeh, et al., 2022, Mohd Aman, Shaari & Ibrahim, 2021). Effective collaboration among energy companies, recyclers, and policymakers can ensure that end-of-life materials are properly collected, processed, and reintegrated into the production cycle. For example, partnerships between energy providers and specialized recycling companies can facilitate the recovery of valuable materials, such as rare earth metals from wind turbines and lithium from batteries. Governments can further support these efforts by implementing regulations that mandate recycling and provide financial support for recycling initiatives.

Policy frameworks and incentives play a critical role in enabling collaboration and supporting the transition to circular economy models. Comprehensive policies that align economic, environmental, and social goals provide a foundation for circular practices. For example, the European Union's Circular Economy Action Plan outlines strategies for reducing waste, improving resource efficiency, and promoting sustainable business models across various sectors, including energy. Such frameworks provide clear guidelines and targets for stakeholders, fostering collaboration and innovation. National and regional policies can also be tailored to address specific challenges within the energy sector, such as promoting the use of renewable energy and ensuring the sustainability of energy infrastructure.

Financial incentives, such as grants, subsidies, and low-interest loans, can encourage companies to invest in circular technologies and practices. For instance, subsidies for research and development can accelerate the innovation of recycling technologies and energy-efficient systems. Tax credits for companies that adopt circular business models further incentivize the transition to sustainable practices (Adejugbe & Adejugbe, 2019, Govender, et al., 2022, Okeke, et al., 2022, Raliya, et al., 2017). Additionally, green public procurement policies, where governments prioritize purchasing goods and services with low environmental impact, can drive demand for circular energy solutions and encourage companies to adopt sustainable practices.

The importance of international collaboration cannot be overstated, given the global nature of energy supply chains. Cross-border partnerships among governments, companies, and research institutions can facilitate the exchange of best practices, technologies, and resources, advancing circular economy models on a global scale (Karad & Thakur, 2021, Leung, et al., 2014, Liu, et al., 2019, Mahmood, et al., 2022). International organizations, such as the United Nations and the International Energy Agency, play a crucial role in fostering collaboration through initiatives that promote sustainable energy and resource management. For example, the United Nations' Sustainable Development Goals (SDGs), particularly Goal 12 on responsible consumption and production, provide a framework for global collaboration in achieving circular economy objectives.

Collaboration among academia, industry, and government is also essential for advancing research and innovation in circular economy models. Research institutions can contribute to the development of new materials, technologies, and methodologies that support circular practices in energy supply chains. Collaborative projects and public-private partnerships can accelerate the commercialization of these innovations, ensuring their practical application in the energy sector. For instance, research into biodegradable materials for solar panels and batteries demonstrates how academic-industry collaboration can drive circularity.

In conclusion, collaboration and stakeholder engagement are indispensable for the successful adoption of circular economy models in energy supply chains. The transition to circularity requires the collective efforts of energy companies, suppliers, governments, consumers, and civil society to redesign supply chains, implement sustainable practices, and create policy frameworks that support resource efficiency and waste reduction. By fostering collaboration and leveraging the expertise and resources of diverse stakeholders, the energy sector can achieve its sustainability goals and contribute to a more resilient and circular economy. Through shared responsibility and coordinated action, stakeholders can overcome challenges, unlock opportunities, and create a sustainable energy future that benefits both society and the environment.

7 Case Studies of Circular Economy in Energy Supply Chains

Circular economy models have begun to reshape the landscape of energy supply chains, offering innovative solutions to resource management, waste reduction, and sustainability challenges. Various energy companies have implemented successful circular economy practices, demonstrating their potential to drive cost efficiency, improve environmental performance, and enhance business resilience. By examining real-world case studies, it becomes evident that the integration of circular economy principles can lead to transformative outcomes for the energy sector.

One notable example of circular economy implementation is Ørsted, a Danish multinational energy company that transitioned from fossil fuels to renewable energy while adopting circular practices across its operations. Ørsted's efforts to build wind farms with a focus on sustainability provide a blueprint for circularity in the energy sector (Tabatabaei, et al., 2022, Tester, et al., 2021, Weldeslassie, et al., 2018, Younger, 2015). The company prioritizes the use of recycled and sustainable materials in turbine production and has implemented processes to recycle turbine blades at the end of their life cycle. By collaborating with suppliers and recycling companies, Ørsted ensures that materials such as rare earth metals and fiberglass are recovered and reused. This approach not only reduces waste but also minimizes the environmental impact of raw material extraction. The lessons learned from Ørsted's experience highlight the importance of designing energy infrastructure for recyclability and fostering partnerships to close material loops.

Another compelling case study is that of Enel, an Italian energy company that has integrated circular economy principles into its business strategy. Enel has implemented innovative practices such as circular city projects, which focus on creating sustainable urban energy systems. For example, in the Circular Smart City project in Brazil, Enel deployed technologies that combine renewable energy generation, energy efficiency, and waste-to-energy systems. The initiative also involved refurbishing aging infrastructure to extend its operational life, thus reducing the need for new resources. Enel's approach underscores the value of combining technological innovation with a circular mindset to address resource inefficiencies in urban energy systems. The company's success illustrates the benefits of engaging multiple stakeholders, including local governments, technology providers, and communities, to achieve circularity.

The example of Vestas, a global leader in wind turbine manufacturing, further demonstrates the potential of circular economy models in energy supply chains. Vestas has committed to producing zero-waste turbines by 2040, leveraging innovative design and manufacturing practices. The company employs modular designs that allow for easier disassembly and recycling of turbine components (Adepoju, Esan & Akinyomi, 2022, Iwuanyanwu, et al., 2022, Griffiths, 2017, Soga, et al., 2016). Additionally, Vestas invests in research and development to identify alternative materials that are both durable and recyclable. By incorporating circular design principles, Vestas has reduced the lifecycle costs of its turbines while minimizing environmental impacts. The company's experience highlights the role of research, innovation, and strategic planning in achieving circularity goals.

Solar energy companies have also embraced circular economy practices to address challenges associated with end-of-life management of photovoltaic (PV) panels. First Solar, a prominent solar panel manufacturer, has implemented a closed-loop recycling program to recover valuable materials such as cadmium and tellurium from decommissioned panels. The recycled materials are then reintegrated into the production of new panels, reducing reliance on virgin resources and lowering production costs (Adenugba & Dagunduro, 2018, Matthews, et al., 2018, Gür, 2022, Jamrozik, et al., 2016). First Solar's approach demonstrates the financial and environmental benefits of designing recycling processes that align with circular economy principles. Moreover, it underscores the importance of considering the entire lifecycle of energy products to create sustainable supply chains.

The oil and gas sector, traditionally associated with linear models, has also witnessed promising circular economy initiatives. Shell, for instance, has incorporated circularity into its operations by focusing on waste reduction and resource efficiency. One of Shell's notable projects involves converting waste gases into biofuels through advanced recycling technologies. This initiative not only reduces greenhouse gas emissions but also provides a sustainable energy source, aligning with the principles of circularity. Shell's experience highlights the potential for circular economy models to drive innovation and sustainability even within industries reliant on finite resources.

The adoption of circular economy models has generated valuable lessons and best practices for the energy sector. One key takeaway is the importance of collaboration among stakeholders. Successful case studies consistently demonstrate that partnerships between energy companies, suppliers, recyclers, governments, and consumers are essential for creating closed-loop systems (Adejugbe, 2021, Chen, et al., 2022, Chukwuemeka, Amede & Alfazazi, 2017, Muther, et al., 2022). Collaboration fosters the exchange of knowledge and resources, enabling stakeholders to address common challenges and achieve shared sustainability goals. For instance, partnerships between recycling companies and energy firms, as seen in the case of First Solar, facilitate the recovery and reuse of valuable materials, reducing waste and production costs.

Another critical lesson is the necessity of designing energy systems and products with circularity in mind. The experiences of Ørsted and Vestas illustrate how incorporating modular and recyclable designs during the manufacturing phase can simplify disassembly and recycling processes at the end of a product's life. Such forward-thinking approaches not only reduce environmental impacts but also enhance the economic viability of circular practices.

Technological innovation emerges as a recurring theme in successful circular economy initiatives. Companies like Enel and Vestas have demonstrated how leveraging advanced technologies such as predictive maintenance, digital twins, and material tracking systems can optimize resource flows and extend the lifespan of energy infrastructure. By investing in research and development, energy companies can discover new materials, processes, and technologies that support circularity, enhancing their competitiveness in an evolving market.

The integration of circular economy models into energy supply chains has had a profound impact on cost efficiency, environmental performance, and business resilience. From a financial perspective, circular practices such as recycling, resource recovery, and lifecycle management reduce material costs and improve operational efficiency. For example, First Solar's closed-loop recycling program has enabled the company to lower production expenses while maintaining a competitive edge in the solar market (Adejugbe, 2021, Chen, et al., 2022, Chukwuemeka, Amede & Alfazazi, 2017, Muther, et al., 2022). Similarly, the use of recycled materials in Ørsted's wind turbines has reduced reliance on expensive raw materials, resulting in cost savings.

Environmentally, circular economy models contribute to significant reductions in waste generation, greenhouse gas emissions, and resource depletion. By prioritizing renewable and recyclable materials, companies like Enel and Shell have minimized their environmental footprint while promoting sustainable resource management. The environmental benefits of circular practices also extend to communities and ecosystems, as demonstrated by Enel's Circular Smart City project, which addresses urban sustainability challenges.

Business resilience is another critical outcome of adopting circular economy models. Companies that embrace circularity are better equipped to navigate resource scarcity, regulatory pressures, and shifting consumer preferences. By fostering innovation and sustainability, circular economy practices enhance a company's ability to adapt to changing market conditions and maintain long-term competitiveness. Vestas' commitment to producing zero-waste turbines positions the company as a leader in sustainable energy solutions, attracting environmentally conscious investors and customers.

In conclusion, case studies of circular economy models in energy supply chains highlight the transformative potential of these practices for sustainable resource management. Companies such as Ørsted, Enel, Vestas, First Solar, and Shell have demonstrated how circularity can drive cost efficiency, improve environmental performance, and enhance business resilience. The lessons learned from these examples emphasize the importance of stakeholder collaboration, innovative design, and technological advancements in achieving circular economy goals. As the energy sector continues to evolve, the adoption of circular economy models will play a pivotal role in creating sustainable and resilient energy systems that benefit both society and the environment.

8 Challenges in Implementing Circular Economy in Energy Supply Chains

The transition to a circular economy in energy supply chains presents a promising pathway to enhancing resource efficiency, reducing environmental impacts, and promoting sustainability. However, despite its potential, the adoption of circular economy principles faces several challenges that hinder its widespread implementation. These challenges span technical, financial, and regulatory barriers, supply chain complexities, and the need for significant investment in circular infrastructure and technology. Overcoming these challenges is crucial to ensuring the successful integration of circular economy models into energy supply chains.

One of the primary barriers to adopting circular economy practices in energy supply chains is the technical challenge of redesigning existing systems and infrastructure to accommodate circular principles. The energy sector, especially traditional fossil fuel-based industries, operates on linear models that focus on extraction, use, and disposal. Transitioning to a circular economy requires rethinking the entire lifecycle of energy systems, from resource extraction to end-of-life management (Agupugo & Tochukwu, 2021, Chenic, et al., 2022, Hoseinpour & Riahi, 2022, Raza, et al., 2019). This often involves redesigning products and infrastructure for greater durability, recyclability, and the ability to reuse materials. Many energy technologies, such as wind turbines, solar panels, and batteries, are designed with limited recyclability in mind, and altering their design to meet circular economy criteria can be technically demanding.

For example, renewable energy technologies like solar panels and wind turbine blades are made from complex materials that are difficult to recycle at the end of their lifecycle. Solar panels contain valuable materials such as silicon, silver, and aluminum, but the process of recovering these materials is not yet widespread or economically viable in many parts of the world. Similarly, wind turbine blades are often made from composite materials that are challenging to break down and recycle. Addressing these technical issues requires substantial innovation and the development of new materials, technologies, and recycling methods that align with circular economy goals.

In addition to technical barriers, financial challenges also pose significant obstacles to implementing circular economy practices in energy supply chains. The initial investment required to redesign energy infrastructure, develop new technologies, and establish recycling systems can be prohibitively expensive. For many energy companies, particularly those in developing economies, the financial burden of transitioning from linear to circular models may be perceived as too high (Adejugbe & Adejugbe, 2018, Oyedokun, 2019, Hossain, et al., 2017, Jharap, et al., 2020). While circular economy practices often lead to long-term cost savings, such as reduced material and waste disposal costs, the upfront capital required to implement these changes is a significant deterrent.

Moreover, many energy companies may not have the financial resources or incentives to invest in circular economy initiatives, particularly when fossil fuel-based systems continue to dominate the market (Tahmasebi, et al., 2020, Teodoriu & Bello, 2021, Wang, et al., 2018, Wu, et al., 2021). The initial costs of adopting circular practices, such as the development of recycling facilities or investment in sustainable materials, may not provide immediate returns, making it difficult for companies to justify these expenditures. As a result, the energy sector may resist circular economy integration unless there is clear financial support, such as government subsidies, grants, or favorable tax incentives.

Regulatory challenges also present a significant hurdle to the adoption of circular economy models in the energy sector. In many countries, existing regulations are still based on traditional linear models of production and consumption, which prioritize resource extraction and waste disposal rather than recycling and reuse (Adenugba, Excel & Dagunduro, 2019, Child, et al., 2018, Huaman & Jun, 2014, Soeder & Soeder, 2021). This regulatory framework can create barriers for companies attempting to adopt circular practices, as they may face obstacles in obtaining permits or meeting compliance requirements related to waste management, recycling, and product design. For instance, regulations surrounding the disposal of decommissioned wind turbine blades or solar panels may not be well defined, making it difficult for energy companies to manage these materials in a circular way.

Additionally, regulatory frameworks often fail to incentivize circular practices or penalize wasteful, linear business models. The lack of clear policies, such as extended producer responsibility (EPR) regulations or regulations promoting recycling and remanufacturing, can discourage energy companies from pursuing circular economy practices. Governments must therefore create and enforce regulations that align with circular economy principles, ensuring that companies have the legal framework and incentives necessary to implement circular practices.

In addition to regulatory challenges, supply chain complexities and integration issues further hinder the implementation of circular economy models in energy supply chains. The energy supply chain is a complex network involving numerous stakeholders, including resource suppliers, manufacturers, logistics providers, and end users. Integrating circular economy principles into this existing supply chain requires significant coordination and collaboration among all stakeholders (Adejugbe & Adejugbe, 2019, de Almeida, Araújo & de Medeiros, 2017, Tula, et al., 2004). However, aligning the interests of different actors in the supply chain can be challenging, especially when they have competing priorities or limited understanding of circular economy benefits.

For example, manufacturers may be hesitant to adopt circular practices if they perceive them as adding complexity or cost to their operations. Similarly, consumers may be unaware of the environmental benefits of circular economy products, and therefore may not demand or support circular products. This misalignment of incentives can slow down the transition to circular supply chains in the energy sector (Ahmad, et al., 2021, Bristol-Alagbariya, Ayanponle & Ogedengbe, 2022, Maraveas, et al., 2022).

Moreover, the global nature of the energy supply chain introduces additional challenges in integrating circular economy models. Materials and components used in energy technologies are often sourced from different parts of the world, and recycling systems may not be standardized or interconnected across borders. As a result, creating a truly circular supply chain requires overcoming geographic, economic, and regulatory differences, which can be a significant barrier to effective integration.

Another critical challenge in implementing circular economy practices in energy supply chains is the need for investment in circular infrastructure and technology. Circular economy principles require the development of new infrastructure to support material recovery, recycling, and remanufacturing. This infrastructure, such as recycling facilities for wind turbine blades, solar panel recycling plants, and advanced waste-to-energy systems, requires substantial capital investment (Adland, Cariou & Wolff, 2019, Oyeniran, et al., 2022, Jafarizadeh, et al., 2022, Shrestha, et al., 2017). Energy companies may struggle to find the financial resources to develop or scale up such infrastructure, especially in regions where recycling technologies are still in the early stages of development.

Investment in circular technologies is also necessary to support the efficient flow of materials through the supply chain. For example, digital technologies such as the Internet of Things (IoT) and blockchain can be used to track materials, optimize resource use, and monitor the condition of energy infrastructure. However, these technologies require substantial investment in research and development, as well as the infrastructure to support them. Without sufficient investment, energy companies may be unable to implement these technologies at scale, limiting their ability to achieve circular economy goals.

To address these challenges, collaboration among stakeholders, including governments, businesses, and consumers, is essential. Governments must provide financial incentives, such as subsidies, tax breaks, and funding for research and development, to encourage companies to invest in circular economy practices. Additionally, clear and supportive regulatory frameworks that promote recycling, remanufacturing, and sustainable design are crucial for fostering the adoption of circular models in energy supply chains (Adland, Cariou & Wolff, 2019, Oyeniran, et al., 2022, Jafarizadeh, et al., 2022, Shrestha, et al., 2017).

Energy companies, in turn, must invest in research and development to innovate new technologies, materials, and processes that support circularity. Collaboration with other industry players, as well as with academic institutions and technology providers, can accelerate the development of solutions that address technical and financial barriers. Moreover, companies must engage consumers in the circular economy transition by educating them about the benefits of circular products and encouraging their participation in recycling and reuse programs.

In conclusion, the implementation of circular economy models in energy supply chains faces several challenges, including technical, financial, and regulatory barriers, as well as supply chain complexities and the need for significant investment in circular infrastructure and technology. Overcoming these challenges requires a coordinated effort among all stakeholders, including governments, businesses, and consumers, to create the necessary conditions for circular economy practices to thrive. By addressing these challenges, the energy sector can transition to a more sustainable, resource-efficient future that benefits both the environment and the economy.

9 Conclusion

In conclusion, the adoption of circular economy models in energy supply chains presents a transformative opportunity for achieving sustainable resource management and addressing the growing environmental challenges within the energy sector. Circular economy principles, such as reducing resource consumption, reusing materials, recycling, and remanufacturing, can significantly reduce waste, enhance resource efficiency, and minimize the environmental footprint of energy production. These models offer a sustainable alternative to the traditional linear economy, which relies heavily on extraction, consumption, and disposal. By embracing circular practices, energy companies can create a more resilient, resource-efficient, and environmentally responsible supply chain.

The integration of circular economy practices into energy supply chains offers numerous benefits, including cost savings from reduced resource consumption, increased operational efficiency, and improved environmental performance. Moreover, circular models align with the growing global demand for renewable energy, as they encourage the sustainable use of materials and energy, promote longer product lifecycles, and foster innovative recycling and repurposing solutions. The synergy between renewable energy sources, such as solar, wind, and bioenergy, and circular economy principles offers a powerful approach to reducing dependence on fossil fuels, promoting sustainability, and improving resource management. However, the transition to a circular economy in energy supply chains is not without its challenges, including technical, financial, and regulatory barriers, as well as the need for significant investment in infrastructure and technology.

Looking to the future, the energy sector must continue to innovate and evolve to fully embrace circular economy practices. This will require collaboration across multiple stakeholders, including governments, businesses, and consumers, to create an ecosystem that supports circularity. Clear policy frameworks, financial incentives, and regulatory changes are essential to encouraging the widespread adoption of circular practices in the energy sector.

Investment in research and development will be critical to overcoming technical challenges, such as designing energy infrastructure for longer lifecycles and improving recycling technologies. Moreover, stakeholders must work together to address the complexities of global supply chains and create interconnected systems that enable the efficient flow of materials.

Ultimately, the full integration of circular economy models into energy supply chains will require systemic change. This change must be driven by a shared commitment to sustainability, innovation, and collaboration. By advancing circular economy principles in energy supply chains, the sector can achieve long-term environmental, economic, and social benefits, contributing to a more sustainable and resilient energy future for generations to come.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[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. Ș., 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.