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Advancing petrophysical techniques for sustainable hydrocarbon extraction: Enhancing resource efficiency and minimizing waste

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Abstract

The hydrocarbon industry is facing increasing pressure to enhance resource efficiency and minimize environmental impacts amidst growing global energy demands. This paper explores the advancements in petrophysical techniques and their significant contributions to sustainable hydrocarbon extraction. Often limited by accuracy and predictive capabilities, traditional methods are being transformed by innovations such as digital rock physics, advanced downhole sensors, and sophisticated seismic imaging. These technologies provide a comprehensive understanding of subsurface formations, enabling precise drilling and optimized resource extraction. The integration of real-time data analytics and machine learning further enhances reservoir management by allowing continuous monitoring and adaptive strategies. These advancements increase hydrocarbon recovery rates, reduce drilling costs, and minimize waste and environmental footprint. This paper provides a detailed analysis of these innovations, their impact on resource efficiency, and practical recommendations for the industry. By investing in cutting-edge technologies, embracing real-time data, adopting predictive modeling, fostering continuous innovation, and prioritizing sustainability, the hydrocarbon industry can achieve a more efficient and environmentally responsible approach to resource management.

Keywords: Petrophysical Techniques; Hydrocarbon Extraction; Resource Efficiency; Real-Time Data Analytics; Machine Learning; Environmental Sustainability

1. Introduction

1.1. Background on Hydrocarbon Extraction

Hydrocarbon extraction, primarily encompassing oil and natural gas exploration and production, has been a cornerstone of global energy supply for over a century. This process involves various stages, including geological surveys, drilling, reservoir engineering, and production operations, each requiring sophisticated technologies and methodologies (Dufour, 2018). Initially, the focus was on maximizing extraction rates and ensuring continuous supply to meet the burgeoning energy demands. As a result, traditional methods often prioritized immediate production gains over long-term sustainability and environmental considerations. Techniques such as conventional drilling, secondary recovery methods, and the use of chemical additives have significantly contributed to the efficient extraction of hydrocarbons. However, these practices also brought about several environmental challenges, including habitat disruption, water contamination, and greenhouse gas emissions (Yang, Sun, Wang, & Qu, 2023).

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The evolution of hydrocarbon extraction has seen the development of more advanced technologies like hydraulic fracturing (fracking) and horizontal drilling (Speight, 2019). These innovations have unlocked previously inaccessible reserves, particularly in shale formations, leading to a surge in production. Despite these advancements, the environmental footprint of hydrocarbon extraction remains substantial. Issues such as methane leakage, induced seismicity, and the vast amounts of water required for fracking have prompted a re-evaluation of extraction practices. The industry's challenge lies in balancing the growing global energy demand with the urgent need to mitigate environmental impacts and ensure long-term sustainability (Brown, 2017).

1.2. Importance of Sustainability in the Hydrocarbon Industry

Sustainability has become an imperative in the hydrocarbon industry, driven by increasing environmental awareness, regulatory pressures, and the global commitment to combat climate change. The Paris Agreement and various national regulations have set ambitious targets for reducing greenhouse gas emissions, which necessitates a shift towards more sustainable extraction practices. As a significant contributor to global emissions, the hydrocarbon industry plays a crucial role in achieving these targets (Silvestre & Gimenes, 2017).

Sustainable hydrocarbon extraction aims to minimize the environmental footprint while optimizing resource efficiency. This involves adopting practices that reduce emissions, prevent spills and leaks, and manage waste effectively (Tabatabaei, Kazemzadeh, Sabah, & Wood, 2022). Enhanced recovery techniques, such as carbon capture and storage (CCS) and the use of renewable energy sources for extraction processes, are being explored to make the industry more sustainable. Furthermore, the integration of digital technologies and data analytics is revolutionizing the way hydrocarbon reservoirs are managed, enabling more precise and efficient extraction with minimal environmental impact (Litvinenko, 2020).

The transition towards sustainable practices is both environmentally and economically beneficial. Companies adopting sustainable methods often experience enhanced operational efficiency, reduced regulatory risks, and improved stakeholder relations. Investors and consumers are increasingly favoring companies that demonstrate a commitment to environmental stewardship, which can enhance a company's market position and financial performance. Therefore, embracing sustainability is not merely a regulatory or ethical obligation but a strategic business decision that can drive long-term success in the hydrocarbon industry.

1.3. Objectives of the Paper

This paper explores the advancements in petrophysical techniques that contribute to sustainable hydrocarbon extraction, emphasizing their role in enhancing resource efficiency and minimizing waste. The objectives are threefold:

- Review Current Petrophysical Techniques
- Analyze Innovations in Petrophysical Techniques
- Evaluate the Impact on Resource Efficiency and Waste Minimization

Through these objectives, the paper intends to highlight the critical role of petrophysical advancements in fostering a sustainable hydrocarbon industry. It will provide insights into how these innovations can be integrated into existing practices to enhance overall efficiency and sustainability. Moreover, the paper will offer practical recommendations for industry stakeholders, including policymakers, researchers, and practitioners, to drive the adoption of sustainable petrophysical techniques. Doing so aims to contribute to the broader discourse on sustainable energy practices and support the industry's transition towards a more environmentally responsible future.

2. Overview of Current Petrophysical Techniques

2.1. Description of Traditional Petrophysical Methods

Petrophysical techniques are fundamental in the exploration and production of hydrocarbons, providing critical insights into the properties of reservoir rocks and fluids (Onita, Ebeh, Iriogbe, & Nigeria, 2023). Traditional petrophysical methods encompass a range of techniques designed to evaluate the porosity, permeability, fluid saturation, and lithology of subsurface formations. Core analysis and well logging are two cornerstone methods used in this field (Holdaway & Irving, 2017).

Core analysis involves extracting cylindrical samples of rock (cores) from the subsurface and examining them in a laboratory setting. This analysis provides direct measurements of rock properties, such as porosity and permeability, which are essential for understanding the storage and flow capacity of the reservoir. Core analysis also includes special

core analysis (SCAL) that focuses on more detailed studies like capillary pressure and relative permeability, crucial for advanced reservoir modeling (Tavakoli, 2018).

On the other hand, well logging involves using downhole tools to measure the physical properties of the rock formations surrounding the wellbore. These measurements are recorded continuously as the logging tool is lowered and raised in the well, creating a log of data that can be interpreted to infer various petrophysical properties (Gooneratne, Li, Deffenbaugh, & Moellendick, 2019). Common well logs include resistivity logs, which measure the electrical resistance of the formation to determine fluid content; gamma ray logs, which identify the lithology by detecting natural radioactivity; and neutron and density logs, which are used to estimate porosity (Liu, 2017).

In addition to these techniques, seismic surveys are employed to create detailed images of subsurface structures. When integrated with well log information, seismic data enhances understanding the reservoir's geometry and continuity. Traditional seismic methods involve generating sound waves at the surface and measuring their reflections from subsurface formations. This data is processed to produce a seismic image, which can be interpreted to identify potential hydrocarbon-bearing structures.

2.2. Challenges and Limitations in Current Practices

While traditional petrophysical methods have been instrumental in the development of the hydrocarbon industry, they are not without their challenges and limitations. One significant challenge is the resolution and accuracy of the data obtained from well logs and seismic surveys. Well logs provide detailed information but only along the wellbore path, which represents a tiny fraction of the entire reservoir. This limitation can lead to uncertainty in reservoir characterization, especially in heterogeneous formations where properties can vary significantly over short distances (Guoqiang, 2021).

Although useful for imaging large subsurface areas, seismic surveys often lack the resolution needed to detect fine-scale features critical for accurate reservoir modeling. The interpretation of seismic data can also be complex and subjective, requiring experienced geophysicists to derive meaningful insights. Additionally, seismic surveys are expensive and time-consuming, which can limit their frequency and scope.

Despite its direct measurement approach, core analysis presents its own challenges. The extraction and handling of core samples can be technically demanding and costly. Furthermore, the representativeness of core samples is often questioned, as the coring process may alter the rock properties, and the samples represent only a small volume of the reservoir. Laboratory conditions also differ from in-situ conditions, potentially leading to discrepancies between measured and actual reservoir properties.

Another limitation of traditional petrophysical methods is the reliance on empirical correlations and assumptions. For example, the interpretation of well log data often depends on established petrophysical models that may not be universally applicable across different geological settings. These models can introduce significant uncertainties, especially in complex reservoirs where the rock and fluid properties do not conform to standard assumptions (Aleardi, 2018).

Environmental and operational challenges further complicate traditional petrophysical practices. Harsh subsurface conditions, such as high temperatures and pressures, can affect the performance of logging tools and the quality of the data acquired. In addition, the presence of complex fluid systems, such as those involving heavy oils or mixed lithologies, can challenge the accuracy of petrophysical measurements and interpretations. Moreover, traditional methods can be invasive and environmentally impactful. Core extraction and extensive seismic surveys can disrupt the subsurface environment, raising concerns about the ecological footprint of these activities. As the industry moves towards more sustainable practices, there is a growing need to minimize the environmental impact of petrophysical operations (Dabros, Pyper, & Castilla, 2018).

The integration of data from different petrophysical methods poses another challenge. Each technique provides valuable but distinct types of information, and combining these datasets into a coherent reservoir model requires sophisticated data integration and interpretation skills. Discrepancies between data sources can lead to conflicting interpretations and uncertainty in decision-making (Smelror, 2020).

Given these challenges and limitations, the industry is increasingly exploring advanced petrophysical techniques that leverage new technologies and methodologies to enhance data accuracy, resolution, and integration. Innovations such as digital rock physics, advanced downhole sensors, and machine learning algorithms are being developed to address

the shortcomings of traditional methods and support more effective and sustainable hydrocarbon extraction. These advancements aim to provide a more comprehensive understanding of reservoir properties, reduce environmental impacts, and improve hydrocarbon production operations' overall efficiency and sustainability.

3. Innovations in Petrophysical Techniques

3.1. New Technologies and Methodologies in Petrophysics

The field of petrophysics has witnessed significant technological advancements, driven by the need to enhance hydrocarbon extraction's accuracy, efficiency, and sustainability. These innovations encompass a range of new technologies and methodologies that have revolutionized traditional practices (Gluyas & Swarbrick, 2021).

One such advancement is the development of digital rock physics. This technique involves creating high-resolution digital models of rock samples using micro-CT scanning and other imaging technologies. These digital models allow for detailed analysis of pore structures and fluid flow characteristics without the limitations of physical core samples. Digital rock physics provides a more accurate representation of reservoir properties, enabling better predictions of hydrocarbon behavior and more effective reservoir management (Saxena et al., 2019).

Another notable innovation is the use of advanced downhole sensors and tools. Modern logging tools are equipped with high-precision sensors that can measure a variety of parameters in real time, including pressure, temperature, and fluid composition. Tools such as nuclear magnetic resonance (NMR) logs provide detailed insights into porosity and fluid types, while formation testing tools can directly sample reservoir fluids under in-situ conditions. These advancements have significantly improved the resolution and reliability of petrophysical data (Hassani & Dackermann, 2023).

Additionally, new methodologies in seismic imaging, such as full-waveform inversion (FWI) and microseismic monitoring, have enhanced the ability to image and characterize subsurface formations. FWI uses the complete seismic wavefield to generate highly detailed subsurface images, improving the accuracy of reservoir models. Microseismic monitoring involves detecting and analyzing small seismic events induced by hydrocarbon extraction activities, providing real-time feedback on reservoir behavior and aiding in the optimization of extraction processes (Bruno, 2023).

3.2. Integration of Advanced Data Analytics and Machine Learning

The integration of advanced data analytics and machine learning (ML) has further transformed petrophysical techniques. The vast amount of data generated from modern logging tools, seismic surveys, and digital rock models requires sophisticated analysis to extract meaningful insights. With their ability to identify patterns and correlations in large datasets, machine learning algorithms have become indispensable in this context.

In petrophysics, ML algorithms are used to enhance data interpretation and reservoir characterization. For example, supervised learning techniques can be applied to well log data to predict lithology and fluid types with greater accuracy. By training ML models on large datasets of historical well logs, these algorithms can learn to recognize complex patterns and make accurate predictions about subsurface properties (A. Mishra, Sharma, & Patidar, 2022).

Unsupervised learning techniques, such as clustering and dimensionality reduction, are also employed to analyze seismic data and identify features that may not be apparent through traditional interpretation methods. These techniques can help detect subtle variations in the seismic response, leading to more precise delineation of reservoir boundaries and identification of potential hydrocarbon-bearing zones (Joshi et al., 2021).

Moreover, the use of artificial intelligence (AI) in predictive modeling has significantly improved the ability to forecast reservoir performance and optimize production strategies. AI models can integrate data from multiple sources, including well logs, seismic surveys, and production history, to create comprehensive reservoir simulations. These simulations enable more accurate predictions of future production rates and help identify optimal extraction strategies that maximize resource recovery while minimizing environmental impact (Ibrahim, Huang, Ahmed, Koo, & El-Shafie, 2022).

Integrating advanced data analytics and machine learning enhances the accuracy and efficiency of petrophysical techniques and facilitates real-time decision-making. Real-time data analysis allows for the immediate adjustment of drilling and production parameters, optimizing hydrocarbon extraction and reducing the risk of operational issues. This

dynamic approach to reservoir management is particularly valuable in complex and heterogeneous reservoirs, where conditions can change rapidly and require continuous monitoring and adaptation (Guo et al., 2021).

3.3. Benefits of These Innovations in Terms of Resource Efficiency and Waste Minimization

The innovations in petrophysical techniques offer substantial benefits in terms of resource efficiency and waste minimization, addressing some of the key challenges faced by the hydrocarbon industry. Enhanced data accuracy and resolution from advanced logging tools and seismic imaging techniques lead to better reservoir characterization and more efficient resource extraction. By accurately identifying the location and extent of hydrocarbon deposits, these innovations reduce the need for unnecessary drilling and minimize the environmental footprint of exploration activities. Precise targeting of hydrocarbon-rich zones improves the efficiency of extraction processes, maximizing resource recovery and reducing waste (Seyyedattar, Zendehboudi, & Butt, 2020).

Digital rock physics and machine learning-driven predictive models contribute to more effective reservoir management by providing detailed insights into reservoir behavior and fluid flow dynamics. These technologies enable the optimization of production strategies, ensuring that hydrocarbons are extracted most efficiently. Operators can implement proactive measures to enhance resource efficiency and prevent wastage by predicting reservoir performance and identifying potential issues before they arise (Bajpai et al., 2022).

Furthermore, the integration of real-time data analysis and AI-driven decision-making supports the implementation of adaptive extraction strategies. Real-time monitoring allows for immediate adjustments to drilling and production parameters, optimizing resource utilization and minimizing the risk of operational disruptions. This adaptive approach is particularly valuable in challenging and dynamic reservoir environments, where traditional static models may fall short.

The environmental benefits of these innovations are also significant. Advanced petrophysical techniques help reduce the environmental impact of hydrocarbon extraction by minimizing the volume of waste generated and preventing environmental contamination. For example, improved reservoir characterization reduces the likelihood of drilling dry wells, which can result in wasted resources and environmental disturbance. Additionally, real-time monitoring and predictive modeling enable operators to detect and mitigate potential issues such as leaks and spills, preventing environmental damage (Onita et al., 2023).

4. Impact on Resource Efficiency and Waste Minimization

4.1. Analysis of How Advanced Techniques Improve Resource Management

The advent of advanced petrophysical techniques has profoundly impacted the hydrocarbon industry, significantly enhancing resource management and minimizing waste. These improvements stem from the increased accuracy, precision, and predictive capabilities offered by modern technologies and methodologies. Enhanced reservoir characterization is one of the primary ways advanced techniques improve resource management (Ghorbani et al., 2023). Traditional methods often provide limited and sometimes inaccurate data, leading to suboptimal drilling decisions and inefficient resource extraction. However, with advanced logging tools, digital rock physics, and sophisticated seismic imaging, operators can now understand the reservoir more comprehensively and accurately. For example, nuclear magnetic resonance (NMR) logs and high-resolution micro-CT scans provide detailed insights into porosity, permeability, and fluid saturations, which are critical for identifying reservoirs' most productive zones (S. Mishra, 2022).

These advancements enable precise targeting of drilling operations, ensuring that wells are placed in the most hydrocarbon-rich areas. By reducing the number of dry wells and minimizing unnecessary drilling, these techniques significantly enhance the efficiency of resource extraction. The ability to accurately delineate reservoir boundaries and identify optimal extraction points reduces the overall environmental footprint of hydrocarbon operations and conserves valuable resources (Sircar, Yadav, Rayavarapu, Bist, & Oza, 2021).

Moreover, the integration of real-time data analytics and machine learning further enhances resource management. Real-time monitoring tools provide continuous data on reservoir conditions, allowing for immediate adjustments to drilling and production strategies. This dynamic approach to reservoir management is particularly beneficial in complex and heterogeneous reservoirs where conditions can change rapidly. By continuously adapting to these changes, operators can optimize production rates and maximize hydrocarbon recovery while minimizing waste.

Machine learning algorithms are crucial in predictive modeling, helping operators forecast reservoir behavior and plan extraction strategies accordingly. By analyzing historical data and identifying patterns, these algorithms can predict future production rates, identify potential issues, and suggest optimal extraction methods. This predictive capability allows for more informed decision-making and proactive management, further improving resource efficiency and reducing waste (Samnioti & Gaganis, 2023).

4.2. Quantitative and Qualitative Benefits

The quantitative and qualitative benefits of advanced petrophysical techniques are significant and multifaceted, impacting both hydrocarbon extraction's economic and environmental aspects. Quantitatively, these advanced techniques lead to increased hydrocarbon recovery rates. Operators can achieve higher production volumes by enabling more accurate reservoir characterization and optimized drilling operations, directly translating to improved economic returns. Furthermore, the reduction in drilling costs is a notable benefit. Advanced techniques minimize the number of dry wells and unnecessary drilling activities, leading to more efficient use of drilling resources and lower operational expenses (Seyyedattar et al., 2020).

Another quantitative benefit is the lower environmental impact. Improved accuracy in reservoir characterization and real-time monitoring reduces the environmental footprint of hydrocarbon extraction. Fewer dry wells and optimized production strategies result in less land disturbance, reduced waste generation, and lower emissions associated with drilling and production activities. Enhanced production efficiency is also a key advantage. The integration of real-time data analytics and machine learning allows for the continuous optimization of production processes. This efficiency leads to higher output with lower input, maximizing the use of available resources and minimizing waste (Djuraev, Jufar, & Vasant, 2017).

Qualitatively, the benefits are equally significant. Advanced techniques improve decision-making by providing high-resolution data and predictive models, which enhance the quality of decisions in reservoir management. Operators can make more informed choices about drilling locations, production strategies, and resource allocation, leading to better overall outcomes. Increased operational flexibility is another qualitative benefit. Advanced techniques allow operators to adapt to changing reservoir conditions in real time. This adaptability is particularly valuable in complex reservoirs where static models may not adequately capture dynamic behaviors (Kroepsch, Maniloff, Adgate, McKenzie, & Dickinson, 2019).

Reduced risk and uncertainty are also crucial qualitative benefits. The precision and accuracy of advanced petrophysical techniques reduce the risk and uncertainty associated with hydrocarbon extraction (Wagner & Uhlemann, 2021). Better reservoir characterization and predictive modeling lower the likelihood of encountering unforeseen issues, enhancing operational reliability and safety. Additionally, these advanced techniques support sustainable practices. The environmental benefits align with the industry's growing emphasis on sustainability. These techniques promote more sustainable and responsible hydrocarbon extraction practices by minimizing waste and reducing the environmental impact of operations (Scheidt, Li, & Caers, 2018).

Furthermore, the adoption of these advanced techniques fosters innovation and technological advancement within the industry. As operators increasingly rely on digital tools and data analytics, there is a growing emphasis on developing new technologies and methodologies to further enhance resource efficiency and waste minimization. This drive for innovation benefits the hydrocarbon industry and has broader implications for other sectors, promoting technological advancements and cross-industry collaborations (Javaid, Haleem, Singh, Suman, & Gonzalez, 2022).

5. Conclusion

The advancements in petrophysical techniques have significantly transformed the hydrocarbon extraction industry, substantially improving resource efficiency and waste minimization. These innovative techniques provide a more accurate and dynamic understanding of subsurface formations through enhanced reservoir characterization, real-time data analytics integration, and machine learning application. Traditional methods, which often relied on limited and sometimes imprecise data, have been augmented by technologies such as digital rock physics, advanced downhole sensors, and sophisticated seismic imaging. These tools enable operators to precisely target hydrocarbon-rich zones, reducing unnecessary drilling and enhancing overall extraction efficiency.

Real-time data analytics and machine learning have further revolutionized the industry by allowing continuous monitoring and adaptive management of reservoirs. The predictive capabilities of machine learning algorithms facilitate better decision-making and proactive management, optimizing production rates and maximizing hydrocarbon

recovery. This dynamic approach ensures that resource extraction is conducted in the most efficient and environmentally responsible manner possible. The integration of these advanced techniques not only enhances economic returns by increasing production volumes and reducing operational costs but also aligns with the industry's growing emphasis on sustainability by minimizing environmental impacts and waste generation.

5.1. Practical Recommendations for the Industry

To fully harness the benefits of these advanced petrophysical techniques, the hydrocarbon industry must adopt several practical recommendations to optimize resource efficiency and minimize waste.

Operators should invest in the latest petrophysical technologies, such as digital rock physics, high-resolution downhole sensors, and advanced seismic imaging tools. These investments will enhance the accuracy of reservoir characterization, enabling more precise targeting of hydrocarbon-rich zones and reducing the incidence of dry wells. Embracing these technologies is crucial for maintaining competitive advantage and achieving sustainable resource management.

The industry must prioritize the integration of real-time data analytics into their operational workflows. Continuous monitoring of reservoir conditions through real-time data allows for immediate adjustments to drilling and production strategies, optimizing resource utilization and minimizing waste. Implementing robust data analytics platforms that can process and analyze large volumes of data in real time will be instrumental in achieving these goals.

Machine learning algorithms and predictive models should be widely adopted to enhance decision-making and proactive reservoir management. By training machine learning models on historical data, operators can improve the accuracy of predictions related to reservoir performance and potential operational issues. These predictive insights enable more informed and strategic decision-making, leading to optimized extraction processes and reduced environmental impact.

The hydrocarbon industry must foster a culture of continuous learning and innovation. This involves staying abreast of the latest technological advancements, investing in research and development, and encouraging collaboration between industry experts, academic institutions, and technology providers. The industry can further enhance resource efficiency and waste minimization by continuously exploring new methodologies and technologies.

Operators should integrate sustainability and environmental responsibility into their core operational strategies. This includes adopting best practices for waste management, reducing emissions, and minimizing the environmental footprint of extraction activities. By prioritizing sustainability, the industry can meet regulatory requirements, enhance corporate reputation, and contribute to the broader goal of environmental stewardship.

In conclusion, the integration of advanced petrophysical techniques offers significant opportunities for improving resource efficiency and minimizing waste in hydrocarbon extraction. By investing in cutting-edge technologies, embracing real-time data analytics, adopting machine learning, fostering innovation, and prioritizing sustainability, the industry can achieve a more efficient, responsible, and sustainable approach to resource management. These practical recommendations provide a roadmap for operators to navigate the challenges of modern hydrocarbon extraction while maximizing economic and environmental benefits.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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