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RESEARCH ARTICLE

OPERATIONAL SUSTAINABILITY: TRANSITIONING CONVENTIONAL DRILLING TO ENVIRONMENT-FRIENDLY PRACTICES

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ABSTRACT

The exigency of integrating environmental sustainability into oil and gas drilling operations forms the crux of this study, which meticulously examines the transition from conventional to eco-friendly drilling practices. This scholarly inquiry aimed to delineate the environmental impacts of traditional drilling methods and elucidate the role that sustainable practices play in modern drilling operations. By employing a rigorous literature review methodology, the study synthesized historical data, technological advancements, policy frameworks, and economic analyses to comprehensively understand the industry's evolution towards sustainability. The findings highlight a significant environmental footprint associated with conventional drilling, prompting an urgent call for operational sustainability. The study reveals that the adoption of sustainable practices, underpinned by technological innovation and strategic policy support, is not only environmentally imperative but also economically viable. It underscores the potential for energy efficiency, waste management, and resource conservation to mitigate the ecological impacts of drilling activities. The conclusion posits that the oil and gas industry stand at a pivotal juncture, where the adoption of sustainable practices is paramount for its long-term viability. The recommendations advocate for a collaborative approach to overcome technological and policy barriers, emphasizing the need for incentivization mechanisms to catalyze the industry's transition towards sustainability. This paper serves as a seminal reference for stakeholders in the drilling industry, providing a roadmap for operational sustainability that harmonizes economic objectives with environmental stewardship.

KEYWORDS

Operational Sustainability, Environmental Impact, Drilling Practices, Technological Innovation, Policy Frameworks, Economic Viability.

1. INTRODUCTION

1.1 The Imperative for Sustainability in Oil and Gas Operations

The imperative for sustainability in oil and gas operations has never been more critical, particularly in the context of drilling activities where environmental stewardship must be a paramount concern (Harkouss, 2020). As the global community becomes increasingly aware of the environmental impacts of industrial activities, the oil and gas industry faces heightened scrutiny over its practices, especially conventional drilling which has historically been a significant source of environmental degradation (Egba et al., 2023).

Conventional drilling operations have been linked to a range of environmental issues, from the contamination of water resources to the disruption of ecosystems. In Lebanon, for instance, environmental regulations have been put in place to manage drilling waste, with a focus on the reduction, reuse, recycling, recovery, and disposal of waste in an environmentally sound manner (Harkouss, 2020). This approach underscores the necessity of integrating environmental considerations into every stage of drilling operations, ensuring that waste management is not an afterthought but a fundamental aspect of operational planning.

The environmental impact of oil and gas extraction in Nigeria further exemplifies the urgent need for a shift towards more sustainable practices. The country's experience with oil and gas extraction has been marred by significant environmental challenges, prompting calls for radical measures to address the deep-seated issues of environmental sustainability (Egba et al., 2023). The Nigerian case highlights the complex interplay between economic development and environmental protection, a balance that is critical to achieving long-term sustainability in the industry.

In response to these challenges, the industry is exploring various technological innovations aimed at reducing the environmental footprint of drilling operations. One such technique is managed pressure drilling (MPD), which offers a range of sustainability benefits, including the containment of reservoir fluids and pressures, reduction in the use of drilling fluids and weighting materials, and the potential for automation and remote operations to reduce human energy expenditure (Dow et al., 2022). By focusing on sustainability key performance objectives (KPOs), MPD and similar technologies represent a shift towards more sustainable drilling practices that can mitigate environmental risks while maintaining operational efficiency.

The transition to sustainable drilling practices is not merely a technical

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challenge but also a policy and economic one. The implementation of environmental regulations, such as those in Lebanon, and the adoption of sustainability metrics, as seen in the application of MPD, require a supportive policy framework and economic incentives to encourage industry compliance and innovation (Harkouss, 2020; Dow et al., 2022). This necessitates a collaborative effort between governments, industry stakeholders, and the broader community to develop and enforce regulations that promote environmental stewardship while recognizing the economic realities of the oil and gas industry.

The urgency for environmental stewardship in drilling activities is evident in the growing body of literature that documents the environmental impacts of conventional drilling and the potential for sustainable practices to mitigate these effects. As the industry moves forward, it must continue to integrate sustainability into its core operations, leveraging technological advancements and policy support to ensure that environmental protection and economic viability are not mutually exclusive goals but are instead seen as complementary components of a sustainable future.

1.1.1 The urgency for environmental stewardship in drilling activities.

The oil and gas sector stands at a critical juncture where the urgency for environmental stewardship is paramount, particularly within the realm of drilling activities. The environmental implications of conventional drilling have been increasingly scrutinized, with a growing consensus on the need for sustainable practices that mitigate ecological impacts (Harkouss, 2020). The call for environmental stewardship in drilling is not merely a response to regulatory pressures but a strategic imperative that aligns with global sustainability goals and the industry's long-term viability.

The environmental hazards associated with drilling activities are multifaceted, ranging from the contamination of water resources to the disruption of terrestrial and marine habitats. In Lebanon, the environmental standards and waste management designs for drilling operations have been identified as crucial for maintaining ecological balance, emphasizing the reduction, reuse, and recycling of waste materials (Harkouss, 2020). This approach is reflective of a broader shift towards a circular economy model within the industry, where the value of resources is maximized, and waste is minimized.

In Nigeria, the environmental impacts of oil and gas extraction have been profound, with significant repercussions for both the environment and local communities. The challenges faced in Nigeria underscore the need for robust environmental laws and policies that can guide the industry towards more sustainable practices (Egba et al., 2023). The Nigerian experience serves as a cautionary tale of the risks associated with inadequate environmental stewardship in drilling activities, highlighting the necessity for radical measures to address these deep-seated sustainability challenges.

Technological innovation plays a pivotal role in advancing environmental stewardship in drilling operations. The adoption of sustainability metrics for managed pressure drilling (MPD) is a prime example of how technology can be leveraged to reduce the environmental footprint of drilling. MPD offers several sustainability advantages, including the containment of reservoir fluids, reduction in the use of drilling fluids, and the potential for automation to decrease human energy use (Dow et al., 2022). By integrating sustainability key performance objectives (KPOs) into drilling operations, MPD represents a significant step forward in reducing the environmental impact of drilling activities.

However, the transition to sustainable drilling practices is not without its challenges. The implementation of environmental stewardship in drilling requires not only technological advancements but also economic and policy support. The development and enforcement of environmental regulations, as seen in Lebanon, are critical to ensuring that companies adhere to sustainable practices (Harkouss, 2020). Similarly, economic incentives can play a vital role in encouraging the adoption of technologies like MPD, which, while offering long-term benefits, may require significant upfront investments (Dow et al., 2022).

The urgency for environmental stewardship in drilling activities is further amplified by the increasing global demand for energy and the corresponding rise in drilling operations. As the industry seeks to meet this demand, it must do so in a manner that is environmentally responsible and sustainable. This requires a concerted effort from all stakeholders, including industry leaders, policymakers, and the scientific community, to collaborate on developing solutions that balance economic growth with environmental protection.

In light of the above, it is evident that environmental stewardship in drilling activities is not just a regulatory requirement but a strategic imperative that is essential for the long-term sustainability of the oil and gas industry. The integration of environmental considerations into drilling operations, the adoption of sustainable technologies, and the support of robust environmental policies are all critical components in addressing the urgent need for environmental stewardship in the industry.

1.1.2 Brief literature review on the impact of conventional drilling on the environment

The environmental impacts of conventional drilling for oil and gas have been a subject of increasing concern and scrutiny. The literature reveals a range of environmental issues associated with drilling activities, from the contamination of groundwater to the abandonment of wells that may become conduits for pollution. Wells and Hester provide a stark illustration of the risks posed by improperly plugged and orphaned wells, particularly in the context of the shale development boom in the Permian Basin (Wells and Hester, 2020). The potential for environmental pollution from these abandoned wells, especially when new drilling occurs nearby, is a significant concern that underscores the need for stringent regulatory oversight and best practice adherence.

The environmental footprint of drilling is not limited to the potential for pollution; it also encompasses the broader impacts on water quality, especially in regions where hydraulic fracturing, or fracking, is prevalent. Brantley's work, although not providing a DOI, highlights the complexity of assessing water quality impacts due to incomplete data from the Pennsylvania Department of Environmental Protection. Despite this, the evidence suggests a low rate of problems per gas well, with management practices improving over time. However, public perception and pushback against fracking are influenced by the density of drilling and fracking activities and their associated risks, such as water contamination and induced seismicity (Brantley, 2015).

A group researchers emphasize the urgent need for best practices in the hydrocarbon exploration and production sector, particularly in sensitive regions like the Amazon (Finer et al., 2013). Their study advocates for the implementation of best practices that integrate engineering criteria with ecological and social considerations. The research reveals that adherence to best practices could significantly reduce the environmental impact of drilling by minimizing the need for infrastructure such as drilling platforms and access roads. Moreover, their cost analysis suggests that following best practices may not only be environmentally prudent but also economically viable.

Some researchers offer a perspective from Malaysia, where the legislative framework and waste management practices are critical to mitigating the environmental impact of offshore drilling activities (Lodungi et al., 2016). The study identifies a lack of comprehensive waste management practices in the Malaysian petroleum industry and contrasts this with practices in other regions. The authors argue for a framework that aligns with Malaysia's legislation and regulations, highlighting the importance of managing the waste produced from drilling activities to protect the environment.

1.2 Historical Overview of Drilling Practices and Environmental Impact

The historical trajectory of drilling practices is marked by technological advancements and a growing awareness of their environmental consequences. The evolution of drilling technologies has been driven by the industry's quest for efficiency and the ability to tap into previously inaccessible reserves. However, this progress has not been without ecological costs. The legacy of a century's worth of drilling, particularly in conventional fields, has left a landscape marked by abandoned wells that pose serious environmental risks (Wells and Hester, 2018). These historical practices have contributed to a situation where today's advancements, such as horizontal drilling and hydraulic fracturing, must contend with the environmental oversights of the past.

The environmental footprint of conventional drilling has been documented in various regions, each with its unique challenges and responses. In the Amazon, for example, the intersection of hydrocarbon activities with sensitive ecosystems and indigenous territories has necessitated a reevaluation of drilling practices. A group researchers demonstrate that the application of best practices in this region could mitigate future impacts by reducing the infrastructure footprint and considering ecological and social factors more fully (Finer et al., 2013).

In Pennsylvania, the experience with fracking has provided valuable lessons on the importance of data transparency and public engagement. The state's efforts to manage the environmental impacts of drilling have

been met with both successes and challenges, as public concerns over water quality and other risks have influenced the social license for drilling activities (Brantley, 2015). This underscores the need for ongoing monitoring, improvement of management practices, and clear communication with affected communities.

Malaysia's approach to managing the environmental impact of drilling waste discharges offers insights into the role of legislative and regulatory frameworks in shaping industry practices. Some researchers highlight the need for a comprehensive waste management framework that not only complies with national legislation but also promotes the efficient and environmentally responsible disposal of waste from drilling operations (Lodungi et al., 2016).

The historical overview of drilling practices and their environmental impact reveals a complex narrative of technological progress, regulatory evolution, and the ongoing challenge of balancing economic development with environmental stewardship. As the industry moves forward, the lessons from the past must inform the development of sustainable drilling practices that minimize environmental harm while meeting the global demand for energy.

1.2.1 Tracing the evolution of drilling technologies and their ecological consequences.

The evolution of drilling technologies has been a journey of innovation, efficiency, and increasing complexity, with significant implications for the environment. The transition from simple vertical wells to sophisticated horizontal drilling and hydraulic fracturing has revolutionized the oil and gas industry. However, this technological advancement has not been without ecological consequences. Innes, Eia, and Nesse compare emissions from different drill-cuttings treatment alternatives, highlighting the environmental benefits of selecting more sustainable options (Innes et al., 2022). Their study underscores the importance of considering the carbon footprint in the disposal and treatment of drill cuttings, a byproduct of the drilling process.

Stern, Webler, and Small delve into the risks associated with unconventional shale gas development, including hydraulic fracturing, commonly known as fracking (Stern et al., 2014). Their research critically examines the environmental, human health, and socioeconomic impacts of this technology. They argue that while shale gas development has economic benefits and the potential to reduce greenhouse gas emissions, it also poses significant environmental risks that require careful management and regulation.

The impact of rig design and drilling methods on the environment has been a focal point for research and development within the industry. Quinlan and Huisman discuss how the design of drilling rigs and the choice of drilling methods can significantly influence the environmental footprint of drilling operations (Quinlan and Huisman, 2011). They emphasize the potential for increased energy efficiency through improved rig design and the utilization of alternative drilling techniques, which can lead to reduced fuel consumption and, consequently, a lower environmental impact.

1.2.2 Review of Scholarly Articles on the Environmental Footprint of Conventional Drilling

The scholarly literature provides a wealth of information on the environmental footprint of conventional drilling practices. The body of work in this area has consistently highlighted the need for improved environmental stewardship and the adoption of more sustainable practices. Innes, Eia, and Nesse contribute to this discourse by demonstrating the environmental advantages of offshore thermal drill-cuttings treatment over conventional methods (Innes et al., 2022). Their emissions assessment offers a clear indication of how technological improvements can lead to more environmentally friendly drilling operations.

Stern, Webler, and Small explore the broader risks of unconventional shale gas development, including the potential for increased long-term greenhouse gas emissions (Stern et al., 2014). Their analysis suggests that while technological advancements have made drilling more efficient, they have also introduced new environmental challenges that must be addressed through improved governance and industry standards.

The research by Quinlan and Huisman on rig design and drilling methods adds to the conversation by showing that environmental considerations are becoming increasingly integral to the design and operation of drilling rigs (Quinlan and Huisman, 2011). Their findings point to the potential for significant environmental improvements through the adoption of energy-efficient rigs and drilling techniques that minimize the ecological impact.

1.3 The Role of Sustainable Practices in Modern Drilling

In the contemporary drilling industry, the adoption of sustainable practices is not merely a regulatory requirement but a strategic imperative that aligns with global environmental goals and market expectations. The concept of sustainability extends beyond environmental conservation, encompassing economic and social dimensions that collectively contribute to the long-term viability of drilling operations. The industry's shift towards sustainability is driven by the need to mitigate the adverse environmental impacts associated with drilling, such as greenhouse gas emissions, water contamination, and ecological disruption, while ensuring that the economic benefits of resource extraction are not compromised (Ravasio et al., 2022).

1.3.1 Defining Operational Sustainability within the Drilling Industry

Operational sustainability within the drilling industry is defined by practices that ensure the efficient use of resources, minimize environmental impact, and maintain the economic viability of drilling activities. This involves the implementation of technologies and processes that reduce the carbon footprint, enhance energy efficiency, and minimize waste generation. Ravasio, Pellegrini, and Quarto propose a CO2 efficiency index as a measure of the environmental-economic efficiency of drilling processes, which could serve as a critical tool for decision-makers in the industry (Ravasio et al., 2022). By optimizing operational conditions, such as the choice of dielectric fluids and electrode materials, the drilling industry can significantly improve its sustainability profile.

1.3.2 Synthesis of Literature on the Intersection of Environmental Stewardship and Economic Viability

The literature on sustainable drilling practices highlights a growing consensus on the need for a balanced approach to environmental stewardship and economic viability. A group researchers provide a semi-quantitative assessment of the environmental impacts of coal mining, emphasizing the need for environmentally friendly operations to maintain the sustainability of the mining sector (Mohsin et al., 2021). The study suggests that while coal mining contributes to economic development, it also poses significant risks to environmental sustainability, necessitating the adoption of cleaner technologies and stricter environmental standards.

A group researchers examine the carbon emissions associated with geothermal drilling projects, offering insights into how operational efficiencies and alternative fuels can reduce the industry's carbon footprint (Al Asy'ari et al., 2022). Their research underscores the potential for significant emissions reductions through the adoption of biodiesel and renewable energy sources, which not only contribute to environmental sustainability but also offer economic benefits in terms of reduced fuel costs and enhanced operational efficiency.

Some researchers discuss the lessons learned from the development of unconventional gas resources in the United States and Australia, highlighting the importance of environmental stewardship in the European context (Wilkinson et al., 2014). The authors argue for collecting robust environmental baseline data, using sound science in decision-making, and implementing collaborative governance as key factors in achieving a sustainable balance between environmental protection and economic growth.

1.4 Aim and Objectives of the Study

The aim of this study is to critically examine and propose a framework for transitioning conventional drilling operations to more environmentally friendly practices without compromising their economic viability. The study is guided by the following specific objectives:

1. To assess the current environmental impacts of conventional drilling operations. This involves a comprehensive review of the ecological consequences of traditional drilling practices, including the assessment of carbon footprint, waste generation, and water and soil contamination to establish a baseline understanding of the environmental challenges posed by conventional drilling.

2. To identify and evaluate sustainable drilling technologies and methods. The study will explore the latest advancements in drilling technology that promise greater environmental stewardship, including the evaluation of alternative energy sources, waste management techniques, and water conservation measures that can be integrated into drilling operations.

3. To analyze the economic implications of adopting sustainable drilling practices. This objective seeks to perform a cost-benefit analysis of transitioning to sustainable drilling practices, considering the initial investment costs, operational cost savings, potential for increased efficiency, and the long-term financial impacts on the drilling industry.

4. To develop strategic recommendations for policy and practice. The study will synthesize the findings from the environmental and economic analyses to formulate strategic recommendations aimed at industry stakeholders, policymakers, and regulatory bodies, providing guidance on the adoption of sustainable practices in drilling operations.

1.5 Delineating the boundaries of the study within the context of existing literature.

This study is situated within the extensive body of existing literature that examines the environmental impacts of drilling operations and the pursuit of sustainability within the oil and gas industry. In delineating the boundaries of this study, it is essential to clarify the scope and the limitations to ensure a focused and coherent analysis.

The study will concentrate on the operational aspects of drilling, specifically looking at the direct environmental impacts such as emissions, waste management, and resource use. It will not extend to the downstream impacts of oil and gas consumption or the broader societal implications of fossil fuel dependency. The temporal scope will be limited to contemporary practices and technologies, with a historical perspective provided only to contextualize current trends and developments.

The geographical focus will be on regions where drilling operations are prevalent and where there is a significant body of research available, to ensure that the findings are relevant and can be generalized to a global context. However, case studies may be drawn from specific countries or regions to illustrate particular points or to provide depth to the analysis.

In terms of the literature, the study will engage with peer-reviewed articles, industry reports, and policy documents that are pertinent to the topics of environmental impact and sustainability in drilling operations. The literature review will be selective rather than exhaustive, aiming to capture the most relevant and recent contributions to the field.

Finally, the study will acknowledge the rapidly evolving nature of both drilling technologies and sustainability practices. As such, while it aims to provide a snapshot of the current state of the art, it will also recognize the provisional nature of any findings, given the pace of innovation and change in the industry.

2. Methodology

2.1 Research Framework for Sustainable Drilling Practices

The research framework for sustainable drilling practices is informed by a comprehensive review of literature that spans financial, environmental, and operational dimensions. Some researchers provide a case study that assesses drilling operations' financial and environmental impacts, emphasizing the need for cost rationalization and environmental stewardship to achieve sustainable development goals (Abdel et al., 2022). This study underscores the importance of evaluating both financial and environmental outcomes of drilling practices, which will be a cornerstone of the research framework in this literature review.

The framework will also draw on the work of who evaluated sustainability practices in the welding process (Fernandes and Ordóñez, 2019). While not directly related to drilling, their literature review and case study analysis approach offers valuable insights into how companies integrate sustainability into operational processes. This perspective will guide the review of literature on sustainable drilling practices, focusing on how the industry has adopted similar sustainability practices.

A group researchers provide a critical discourse on sustainability reporting in the upstream oil and gas industry, highlighting the discrepancies between awards and actual sustainability practices (Kwarto et al., 2021). This systematic literature review approach will inform the critical appraisal of sustainability reports within the drilling industry, examining the veracity and efficacy of reported sustainability practices against actual operational outcomes.

Finally, the work of on the environmental and social sustainability in the UK construction industry offers a framework based on the Triple Bottom Line, which can be adapted to the drilling industry (Misopoulos et al., 2023). Their systematic literature review approach, focusing on environmental and social aspects of sustainability, will be mirrored in this study to ensure a balanced review that covers all dimensions of sustainability in drilling practices.

2.2 Inclusion and Exclusion Criteria for Case Studies and Literature

The inclusion criteria for this literature review will be stringent to ensure the selection of relevant and high-quality studies. Peer-reviewed articles that directly address sustainable drilling practices, such as those will be prioritized (Abdel et al., 2022). The review will include studies that offer a comprehensive insight into sustainable practices' environmental and economic impacts, as well as analyses of policy implications and the role of technological advancements in promoting sustainability in drilling operations.

Conversely, the exclusion criteria will filter out literature that does not focus on drilling operations or lacks a clear connection to sustainability. Studies that do not address the interplay between economic, environmental, and social dimensions, or fail to critically appraise the efficacy of sustainability practices, will be omitted. This approach ensures that the literature review remains focused and relevant, providing a solid foundation for understanding the current landscape of sustainable drilling practices.

2.3 Data Collection on Environmental Impact and Mitigation Strategies

The data collection process for assessing the environmental impact and mitigation strategies in sustainable drilling practices is critical to this research. Some researchers propose a novel model for real-time monitoring of drilling activities, emphasizing the importance of engineering and data-led approaches to sustainability (Samuel et al., 2022). This model, which uses neural networks and the bat algorithm for optimization, provides a comprehensive method for quantifying complex indicators and variables associated with drilling operations. The approach by will inform the data collection methodology for this study, particularly in the real-time monitoring of environmental impacts as drilling operations occur (Samuel et al., 2022).

A group researchers contribute to the data collection framework by presenting a water stewardship evaluation model specifically for oil and gas operators (Li et al., 2023). Their two-parameter based Quadrant Plot is a practical, quantitative method that utilizes both private and public data to evaluate the performance of operators in minimizing the negative impacts of freshwater use. This model will be integrated into the data collection strategy for this study, enabling a quantifiable assessment of water management practices in drilling operations.

2.4 Analytical Methods for Assessing Sustainability Metrics

The analytical methods for assessing sustainability metrics in drilling operations must be robust and comprehensive. While do not provide specific models or methods, their work underscores the importance of identifying and implementing mitigation strategies for environmental impacts, such as sustained casing pressure in shale wells, and improving the usefulness of environmental information for decision-making in organizations (Combs et al., 2018; Perkins, 2018). These studies highlight the need for a multi-faceted approach to analysis, which includes the technical and environmental aspects and the organizational and decision-making processes that influence sustainability in drilling operations.

3. Results

3.1 Comparative Analysis of Conventional vs. Sustainable Drilling Operations

The transition from conventional to sustainable drilling operations is pivotal in reducing the environmental footprint of the oil and gas industry. A comparative analysis reveals significant differences in the carbon footprint and overall sustainability between these two approaches. In other study, researchers provide a comprehensive analysis of carbon emissions in conventional smallholder operations versus innovative large-scale farming, which can be extrapolated to the drilling industry (Hu et al., 2021). Their findings suggest that while large-scale operations can reduce carbon footprint per area, they may increase it per unit of product when the entire supply chain is considered. This insight is crucial for the drilling industry, as it indicates that a holistic view of the supply chain is necessary when assessing the sustainability of drilling operations.

Some researchers explore the effects of process parameters on conventional drilling compared to abrasive water jet drilling (Varanasi, 2023). Their study, which focuses on material removal rates and hole taper, provides a technical comparison that can inform the evaluation of

drilling efficiency and environmental impact. The findings from this study suggest that alternative drilling techniques, such as abrasive water jet drilling, could offer more sustainable options by reducing material waste and energy consumption.

A group researcher compares conventional drilling to helical milling for hole making in Ti6Al4V titanium alloy under dry conditions, highlighting the sustainability advantages of helical milling (Akula et al., 2021). The study demonstrates that helical milling results in lower thrust force, superior surface finish, and reduced burr size, all of which contribute to a more sustainable drilling operation. These technical advantages are directly applicable to the drilling industry, where reducing the environmental impact of drilling operations is a growing concern.

The comparative analysis of these studies underscores the potential for sustainable drilling practices to significantly reduce the environmental impact of drilling operations. By adopting innovative techniques and considering the entire supply chain, the drilling industry can move towards more sustainable operations that minimise carbon emissions and optimize resource use and waste management.

3.2 Identification of Best Practices in Operational Sustainability

Operational sustainability in the drilling industry is a multifaceted challenge that requires a comprehensive approach to identify and implement best practices. Siddiquee et al. (2024) provide a valuable framework for sustainable supplier selection in emerging economies, which is directly applicable to the drilling industry. Their study employs a multi-criteria decision-making (MCDM) approach using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) in a fuzzy environment. This approach allows for the evaluation of suppliers based on their green performance, including energy efficiency, waste management, and carbon footprint reduction. The application of this model in the drilling industry could facilitate the selection of suppliers that adhere to the highest standards of environmental stewardship, thereby enhancing the overall sustainability of drilling operations.

Berardi and Giustolisi address the issue of water conservation in water distribution networks, which is a critical aspect of sustainable drilling practices (Berardi and Giustolisi, 2016). Their research focuses on reducing background leakage in urban water distribution networks, which has significant implications for conserving water resources and reducing the carbon footprint associated with water abstraction, treatment, and pumping. By applying the principles from this study, drilling operations can minimize water waste and enhance the efficiency of water use, which is essential for sustainable resource management.

The identification of best practices in operational sustainability for the drilling industry, therefore, involves the integration of advanced decision-making models for supplier selection and the adoption of water conservation techniques. These practices contribute to the environmental performance of drilling operations and support the industry's long-term economic viability and social responsibility.

3.2.1 Energy Efficiency and Carbon Footprint Reduction

The drilling industry is increasingly focusing on energy efficiency and carbon footprint reduction to align with global sustainability goals. A group researchers discuss the potential for greenhouse gas (GHG) reduction through the digitalization of rig operations (Ferrari et al., 2021). By analyzing power needs and operational conditions, their system provides targets for low emission operations, offering clear instructions on how to utilize diesel generators efficiently. This approach ensures operational safety and promotes emissions reduction, highlighting the role of digitalization in achieving energy efficiency in drilling operations.

Kurniadi, Ryan, and Hamidon outline a strategy for reducing the environmental footprint of hydraulic fracturing operations (Kurniadi et al., 2023). Their paper emphasizes the importance of energy optimization, logistics optimization, material conservation, and technology initiatives to reduce CO2 emissions. The authors argue that these strategies, when implemented, can significantly reduce the cost of well delivery while boosting local economies, demonstrating that environmental and economic benefits can go hand in hand.

Some researchers present a case for remote operations and drilling automation as a sustainable pathway to operational efficiency and carbon emissions reduction (Umeonaku et al., 2023). Their study showcases the value of remote operations in optimizing drilling and logging services, which was particularly evident during the Covid-19 pandemic. The adoption of such technologies not only enhances safety and cost-saving but also contributes to the industry's efforts to achieve net-zero global carbon emissions.

The collective insights from these studies suggest that the drilling industry can achieve substantial gains in energy efficiency and carbon footprint reduction by embracing digitalization, optimizing energy and logistics, conserving materials, and leveraging technology. These practices represent a shift towards more sustainable drilling operations, significantly impacting the industry's environmental and economic performance.

3.2.2 Waste Management and Resource Conservation

Effective waste management and resource conservation are critical components of operational sustainability in the drilling industry. The construction industry, which shares several operational parallels with drilling, provides a useful model for waste management practices. Kareem, Asa, and Lawal emphasize the importance of strategic solid waste resource management planning, which is adaptable to changing economic, social, and environmental conditions (Kareem et al., 2015). Their study advocates for a comprehensive strategy that includes resource conservation to minimize waste generation, offering both environmental benefits and economic gains. By applying these principles to the drilling industry, companies can improve their waste management practices, thereby reducing their environmental footprint and enhancing sustainability.

Singh and Pant introduce a novel waste-to-waste management strategy that utilizes waste glass for polyolefin degradation, a process that can be adapted for managing plastic waste in drilling operations (Singh and Pant, 2018). Their research demonstrates that mechanochemical treatment of waste glass can facilitate the thermal pyrolysis of polyolefin, leading to an improved quality of the resultant products. This innovative approach not only contributes to resource conservation but also promotes the recycling and reuse of post-consumer waste, aligning with the principles of a circular economy.

The World Health Organization's guidance for after-action review (AAR) provides a framework for assessing the effectiveness of waste management and resource conservation practices (World Health Organization, 2019). This process involves a systematic review of actions taken in response to an event, allowing organizations to identify best practices and areas for improvement. Implementing AAR in the drilling industry can help companies to evaluate their waste management strategies and make informed decisions to enhance their sustainability efforts.

The drilling industry can benefit from adopting waste management and resource conservation practices that have proven successful in other sectors. By integrating comprehensive planning, innovative recycling techniques, and systematic evaluation processes, drilling operations can achieve greater sustainability, reduce their environmental impact, and contribute to a more sustainable future.

3.3 Economic Analysis of Transitioning to Sustainable Practices

The economic implications of transitioning from conventional to sustainable drilling practices are multifaceted, encompassing initial capital outlay, operational costs, and long-term financial impacts. Kopsidas, Giannopoulou, and Zarotiadis provide a methodological framework for conducting cost-benefit analyses (CBA) in the context of drilling operations in the Eastern Mediterranean (Kopsidas et al., 2023). Their approach underscores the importance of considering socioeconomic well-being and environmental impacts when evaluating investment plans. This methodology is particularly relevant for the drilling industry as it seeks to balance economic growth with environmental stewardship.

A group researchers explore the concept of Non-Productive Time (NPT) and its financial ramifications within well construction costs (Ajayi et al., 2022). Their study highlights the potential for cost savings through the reduction of NPT, which is often a significant portion of total drilling expenses. By focusing on best-in-class operational procedures and data analysis, the authors demonstrate how prudent management of drilling operations can lead to substantial cost reductions, even amidst fluctuating crude oil prices. This research suggests that sustainable drilling practices, which inherently aim to minimize waste and inefficiency, could contribute to a decrease in NPT and thus enhance the economic viability of drilling projects.

Azunna and Botes discuss the broader concept of sustainable livelihoods, which, while not directly related to drilling, offers insights into the importance of considering the long-term sustainability of economic

practices (Azunna and Botes, 2020). Their analysis of sustainable livelihood capitals in the context of women's development in Nigeria provides a lens through which the drilling industry can view its transition to sustainability: as an investment in the long-term economic and social capital of the regions in which it operates.

The transition to sustainable drilling practices presents both challenges and opportunities from an economic standpoint. The adoption of CBA methodologies, a focus on reducing NPT, and an appreciation for the long-term benefits of sustainable practices can guide the drilling industry towards a more economically and environmentally sustainable future.

3.3.1 Cost-Benefit Analysis of Sustainable Drilling Practices

The oil and gas sector faces increasing pressure to adopt sustainable drilling practices while being a cornerstone of the global energy supply. The economic feasibility of such a transition hinges on a meticulous cost-benefit analysis (CBA) that weighs the upfront costs against long-term gains from environmental stewardship and resource efficiency.

Sampson, Akpabio, and Anyadiagwu delve into the economic implications of gas reinjection, a sustainable practice, for enhanced oil recovery in the Niger Delta (Sampson et al., 2020). Their study underscores the potential for sustainable practices to mitigate environmental harm and bolster economic returns. As demonstrated in their case study, the application of gas reinjection techniques reveals an increase in the net present value (NPV) and internal rate of return (IRR), signifying a positive economic outcome from sustainable drilling operations.

Rodhi, Anwar, and Wiguna contribute to the discourse by examining risk factors in oil and gas projects (Rodhi et al., 2017). Their review emphasizes the complexity of risks inherent in the industry, including those that may impede sustainable development. By integrating risk analysis with CBA, they advocate for a holistic approach that aligns with sustainable development goals. Their findings suggest that addressing risk factors through sustainable practices not only mitigates potential environmental and social impacts but also aligns with economic objectives.

The economic analysis of sustainable practices is incomplete without considering the social dimensions of sustainability. Azunna and Botes explore the concept of sustainable livelihoods, which, although not directly related to drilling practices, provides a framework for understanding the broader economic benefits of sustainability (Azunna and Botes, 2020). Their research on sustainable livelihood capitals in Nigeria offers insights into how sustainable practices can contribute to community development and women's empowerment, indirectly supporting the economic stability of regions dependent on the oil and gas industry.

In synthesizing these perspectives, it becomes evident that sustainable drilling practices, when analyzed through the lens of CBA, offer a compelling economic case. The initial costs associated with implementing sustainable technologies and processes are balanced by the long-term benefits of enhanced recovery rates, reduced environmental liabilities, and improved social outcomes. The integration of risk analysis into CBA further strengthens the argument for sustainability by highlighting the potential for cost savings through risk mitigation.

The transition to sustainable drilling practices is not merely a response to environmental concerns but a strategic economic decision. As the industry moves forward, it is imperative to continue refining CBA methodologies to capture the full spectrum of benefits sustainable practices bring. The economic viability of sustainability in drilling is clear; the challenge lies in effectively communicating and implementing these practices across the industry.

4. Discussion

4.1 Barriers to Implementing Sustainable Drilling Practices

The transition to sustainable drilling practices within the oil and gas industry is fraught with barriers that range from technological limitations to economic and policy constraints. These barriers often stem from the inherent complexities of drilling operations, the high costs associated with adopting new technologies, and the regulatory environment that can either hinder or facilitate change.

Technological challenges are at the forefront of these barriers. Some researchers discuss the technical difficulties associated with preventing sustained casing pressure in shale wells, a problem that poses significant environmental risks and operational challenges (Combs et al., 2017). The study highlights the need for innovative solutions to mitigate these pressures effectively, which is a critical aspect of sustainable drilling practices. However, the development and implementation of such technologies can be cost-prohibitive and require substantial investment in research and development.

Horvat addresses both the technological and regulatory barriers in the context of subsea well access and completions (Horvat, 2019). The editorial points out that while there are opportunities for more sustainable methodologies in offshore drilling, the adoption of these practices is often slowed by regulatory frameworks that do not keep pace with technological advancements. Moreover, the high-risk nature of offshore operations necessitates stringent safety standards, which can complicate the introduction of new, unproven technologies.

A group researchers provide a broader perspective on sustainable energy production, including discussions relevant to the oil and gas industry (Al-Kayiem et al., 2014). The collection of studies within this publication underscores the multifaceted nature of sustainability barriers, from energy efficiency to the integration of renewable energy sources in traditional fossil fuel-based operations. These studies collectively suggest that a holistic approach is required to overcome the barriers to sustainability, one that encompasses technological innovation, economic incentives, and supportive policy frameworks.

The economic implications of transitioning to sustainable drilling practices cannot be overstated. The initial capital outlay for new technologies, the potential for operational disruptions during the transition phase, and the uncertain return on investment contribute to the industry's hesitancy. Furthermore, policy constraints, such as subsidies for traditional energy sources and a lack of incentives for sustainable practices, exacerbate the economic barriers.

The barriers to implementing sustainable drilling practices are significant and multifaceted. Overcoming these barriers will require concerted efforts from industry stakeholders, policymakers, and the scientific community. Technology development investments, regulatory reforms, and economic incentives are essential to facilitate the shift towards more sustainable drilling operations. As the industry navigates these challenges, it must balance the immediate costs with the long-term benefits of sustainability, not only for the environment but also for the industry's own economic resilience and public image.

4.1.1 Technological Challenges in Implementing Sustainable Drilling Practices

Many technological challenges impede the transition towards sustainable drilling practices in the oil and gas industry. These challenges stem from the inherent complexities of drilling operations, the need for advanced engineering solutions, and the integration of new technologies into existing frameworks. Epelle and Gerogiorgis comprehensively review the technological advances and the persistent challenges that characterize the current state of oil and gas drilling systems engineering (Epelle and Gerogiorgis, 2020). They emphasize the need for multidisciplinary approaches and the adoption of Process Systems Engineering (PSE) methodologies to overcome these challenges, which range from geological and climatic to technical and operational.

The urgency to address these technological challenges is further compounded by the industry's push towards digitalization and energy efficiency. Ivanova discusses the role of digital technologies in oil and gas production, highlighting their potential to optimize energy use and enhance sustainability (Ivanova, 2023). The implementation of smart production technologies, including Industry 4.0 innovations, is crucial for strategic and financial sustainable development. However, the integration of these technologies requires significant changes in enterprise strategies and operational models, which can be a daunting task for many organizations.

Moreover, the drive towards a net-zero carbon future presents its own set of technological hurdles. Choo, Noviasta, and Hakim explore the implementation of remote operations in directional drilling and measurement/logging while drilling (DD & M/LWD) as a strategy to reduce carbon emissions (Choo et al., 2022). Their research indicates that such innovative approaches can lead to substantial CO2 emission reductions. However, the deployment of these digital collaborative services necessitates robust connectivity and the centralization of skilled engineers, which can be challenging in remote or underdeveloped regions.

The technological challenges in sustainable drilling are not merely about adopting new technologies but also about the integration and optimization of these technologies within the existing oil and gas

infrastructure. This requires a concerted effort from all stakeholders, including engineers, policymakers, and the workforce, to foster an environment conducive to innovation and change. The industry must navigate these challenges with a forward-thinking mindset, leveraging the advancements in digital technology and engineering to pave the way for more sustainable drilling practices.

The path forward involves addressing the technical complexities of well drilling for fossil fuel production, which has become increasingly important in light of climate change concerns. The industry must continue to explore pressing technical problems and seek PSE-and/or CFD-relevant solutions that can be applied to optimize drilling operations. The versatility of novel PSE-based approaches for optimization and control must be harnessed to tackle contemporary problems, thereby enabling the industry to meet its sustainability goals.

The technological challenges in implementing sustainable drilling practices are multifaceted and require a multidisciplinary approach to resolve. The industry must embrace digital transformation, optimize energy efficiency, and innovate remote operations to achieve sustainability targets. While the challenges are significant, the potential rewards in terms of environmental stewardship and operational efficiency are too great to ignore. The industry's commitment to overcoming these challenges will be a testament to its resilience and dedication to a sustainable future.

4.1.2 Economic and Policy Constraints in Sustainable Drilling Practices

The oil and gas industry's shift towards sustainable drilling practices is a technological journey and a path fraught with economic and policy constraints. These constraints often manifest as formidable barriers to the adoption of environmentally friendly practices in the sector. Walter delves into the discourse surrounding fossil fuels, highlighting how misinformation and corporate interests can shape policy decisions and economic strategies, often to the detriment of sustainable practices (Walter, 2018). The study underscores the influence of corporate narratives in maintaining the status quo, which can hinder the implementation of sustainable drilling due to perceived economic risks and policy inertia.

The economic constraints are multifaceted, ranging from the high initial costs of sustainable technologies to the volatility of oil prices, which can make investments in sustainability less attractive. Companies often face the dilemma of balancing short-term financial performance with long-term environmental goals, a challenge exacerbated by shareholder expectations and market pressures. Furthermore, the existing infrastructure for fossil fuel extraction and processing is deeply entrenched, representing a significant sunk cost that companies are reluctant to write off in favor of greener alternatives.

Policy barriers, on the other hand, are equally challenging. The regulatory environment can be slow to adapt to the needs of sustainable drilling, with legislation often lagging behind technological advancements. Al-Kayiem, Brebbia, and Zubir discuss the broader context of energy and sustainability, suggesting that policy frameworks need to be more conducive to the adoption of renewable energy sources and sustainable practices (Al-Kayiem et al., 2014). Policies that favor fossil fuel industries through subsidies or tax breaks can distort the market, making it harder for sustainable drilling technologies to compete on a level playing field.

Moreover, the geopolitical landscape plays a crucial role in shaping energy policies. National interests and the strategic importance of oil and gas reserves can lead to policy decisions that prioritize energy security over environmental concerns. This can result in a regulatory environment that is resistant to change, creating additional hurdles for companies seeking to transition to sustainable drilling practices.

The interplay between economic and policy constraints is complex, as they often reinforce each other. Economic barriers can lead to a lack of political will to enact stringent environmental regulations, while restrictive policies can stifle innovation and investment in sustainable technologies. Overcoming these constraints requires a concerted effort from all stakeholders, including industry leaders, policymakers, and the public. It calls for a reevaluation of economic models to account for the true cost of environmental degradation and a policy shift towards incentivizing sustainable practices.

In conclusion, the economic and policy constraints facing the oil and gas industry in its transition to sustainable drilling practices are significant. They require a strategic approach that addresses both the immediate financial implications and the long-term policy changes needed to support a sustainable future. While the challenges are daunting, the potential benefits of a more sustainable drilling industry – for both the environment and the economy – make it an endeavor worth pursuing. The industry's ability to navigate these constraints will be a critical factor in its success in achieving sustainability goals.

4.2 Strategic Approaches to Overcome Barriers

The oil and gas industry's journey towards sustainability is complex, with myriad barriers that need to be strategically navigated. Technological innovation, competitive market dynamics, and the digital revolution are key areas where strategic approaches can significantly impact the industry's sustainable transformation.

Das underscores the technological advancements in high-pressure/high-temperature (HP/HT) operations, which are critical for accessing untapped reserves that could potentially meet the global energy demand in a more sustainable manner (Das, 2023). The strategic approach here is not just about developing new technologies but also about ensuring that these technologies are cost-effective, safe, and environmentally sound. The industry's focus on monetizing HP/HT reservoirs is a testament to its commitment to finding solutions that balance economic viability with environmental responsibility. This balance is crucial for the industry's long-term sustainability and requires a continuous investment in research and development to refine these technologies and make them more accessible.

In the competitive landscape, Laari, Töyli, and Ojala highlight the significance of green supply chain management as a strategic differentiator for logistics service providers (Laari et al., 2018). They argue that integrating environmental considerations into business operations can enhance a company's competitive position, even if the financial benefits are not immediately evident. This approach positions environmentally proactive companies ahead of the curve in an industry often scrutinized for its ecological impact. This strategic approach involves not only compliance with existing regulations but also going beyond them to establish a reputation for environmental stewardship. By doing so, companies can not only mitigate risks but also capitalize on new opportunities that arise from a growing market for environmentally responsible energy sources.

The digital transformation of the industry, as discussed is another critical area where strategic approaches can lead to substantial improvements in sustainability (Zborowski et al., 2018). The adoption of data analytics, artificial intelligence, and machine learning can lead to more efficient resource management, reduced waste, and lower emissions. However, this requires a cultural shift within organizations to value and understand the potential of digital tools. Companies need to invest in training and development to equip their workforce with the necessary skills to implement and benefit from these technologies. Moreover, collaboration across the industry can accelerate the adoption of best practices and foster a culture of innovation and continuous improvement.

These strategic approaches are interconnected and reinforce each other. Technological innovation can be enhanced by digital capabilities, while competitive strategies can be informed by the insights derived from advanced analytics. The industry's ability to overcome barriers to sustainability lies in its willingness to adopt a holistic approach that considers technological, economic, and cultural dimensions. By doing so, it can navigate the complexities of the transition to sustainable practices and emerge as a leader in the global effort to achieve a more sustainable future.

The strategic approaches outlined by Das, provide a roadmap for the oil and gas industry to overcome the barriers to sustainability (Das, 2023). These approaches emphasize the need for innovation, competitive ecological management, and digital transformation, all of which are essential for the industry to meet the dual challenges of energy demand and environmental protection. As the industry moves forward, these strategies will be critical in shaping its role in a sustainable energy landscape.

4.2.1 Incentivization and Policy Support

In the quest for operational sustainability within the oil and gas industry, incentivization and policy support play pivotal roles. These mechanisms are not only drivers of innovation but also serve as a bridge between the current state of industrial practices and the envisioned future of environmental stewardship and economic viability. The literature provides insights into how these tools can be effectively utilized to foster sustainable drilling practices.

A group researchers delve into the governance structures that underpin sustainable innovation in the upstream oil and gas sector in Indonesia (Aprizal et al., 2022). They argue that government policies and incentives are critical in steering the industry towards sustainable practices. The study highlights the Indonesian government's role in creating a conducive environment for sustainable innovation through fiscal incentives, regulatory support, and direct investment in green technologies. These policies are not just about encouraging compliance but also about inspiring companies to exceed the minimum requirements and strive for excellence in sustainability. The authors suggest that such an approach can lead to a competitive advantage in the global market, where sustainability is increasingly becoming a benchmark for investment and consumer preference.

Levy and Gopalakrishnan provide a broader perspective on the role of policy in promoting ecological sustainability and community resilience, particularly in the aftermath of environmental disasters like the 2010 Deepwater Horizon oil spill (Levy and Gopalakrishnan, 2010). Their analysis underscores the importance of policy interventions that are not only reactive but also proactive in preventing such incidents. The authors advocate for a policy framework that integrates economic, environmental, and social objectives, thereby ensuring that the industry's growth does not come at the expense of ecological integrity or community well-being. This integrated approach is essential for building a resilient industry capable of withstanding and adapting to the challenges posed by a dynamic global environment.

The insights from these studies suggest that incentivization and policy support should be multifaceted, targeting various aspects of the industry's operations. Fiscal incentives, such as tax breaks and subsidies for clean technology, can lower the financial barriers to adopting sustainable practices. Regulatory support, including clear guidelines and standards for environmental performance, can provide a roadmap for companies to follow. Furthermore, direct investment in research and development can spur innovation in green technologies, making them more viable and accessible.

However, the implementation of these policies is not without challenges. There is a need for a delicate balance between incentivization and regulation, ensuring that policies are stringent enough to protect the environment while also being flexible enough to accommodate the industry's economic realities. Moreover, the global nature of the industry requires international cooperation in policy formulation and enforcement, as sustainability is a concern that transcends national boundaries.

The literature suggests that incentivization and policy support are indispensable tools for achieving operational sustainability in the oil and gas industry. These mechanisms can catalyze the transition to sustainable drilling practices by lowering barriers, guiding corporate behavior, and fostering innovation. As the industry continues to evolve, the role of policy in shaping its trajectory will remain a subject of critical importance.

4.2.2 Technological Innovation and Collaboration

The transition towards sustainable drilling practices in the oil and gas industry is not merely a matter of regulatory compliance or environmental stewardship; it is increasingly recognized as a strategic imperative that hinges on technological innovation and collaboration. The past decades have witnessed a significant evolution in drilling technologies, from the advent of rotary drilling to the sophisticated automated systems of today. These advancements have enhanced operational efficiency and reduced the environmental footprint of drilling activities (Edmundson, 2019). However, the path forward demands a concerted effort to leverage technology to further reduce the industry's carbon footprint and ensure the conservation of resources.

Technological innovation in the oil and gas sector has often been driven by the need to access more challenging reserves, improve recovery rates, and reduce costs. The development of non-intrusive technologies for brownfield redevelopment exemplifies this drive, as operators seek to extend the life of existing fields without the environmental disruption of new drilling (Yeap et al., 2020). These technologies, which include advanced seismic imaging, enhanced oil recovery (EOR) techniques, and smart well technologies, have the potential to transform brownfields into models of efficiency and sustainability.

The role of digitalization in driving sustainability cannot be overstated. Digital technologies such as big data analytics, the Internet of Things (IoT), and artificial intelligence (AI) are enabling operators to optimize drilling operations, monitor environmental impact in real-time, and predict equipment failures before they occur. This predictive capability not only prevents spills and other environmental hazards but also minimizes downtime and maximizes the use of resources. For instance, the use of digital twins—a virtual representation of physical assets—allows for the simulation of drilling operations, enabling the fine-tuning of processes to achieve optimal performance with minimal waste (Edmundson, 2019).

Collaboration is equally critical to the success of technological innovation. The complexity of modern drilling operations often requires expertise from various disciplines, necessitating a collaborative approach to problem-solving. Collaboration can take many forms, from joint ventures and partnerships to industry consortia and academic-industry collaborations. These collaborative efforts can accelerate the development and deployment of new technologies, share risks, and pool resources for research and development.

The industry has also seen the rise of open innovation platforms, where companies share challenges with a broader community of innovators to crowdsource solutions. Such platforms can lead to unexpected breakthroughs and foster a culture of continuous improvement. Moreover, collaboration with regulatory bodies and environmental organizations can help align technological developments with environmental goals, ensuring that innovations contribute positively to sustainability targets.

However, the adoption of new technologies is not without challenges. The upfront costs can be significant, and there is often a lack of skilled personnel to implement and manage these technologies. Moreover, the industry's conservative nature can lead to resistance to change, particularly when the benefits of new technologies are not immediately apparent. To overcome these barriers, the industry must invest in technology and the people who will use it. This includes training and development programs to build a workforce capable of operating in a high-tech, sustainable drilling environment.

The future of sustainable drilling in the oil and gas industry is inextricably linked to technological innovation and collaboration. By embracing digital technologies and fostering a collaborative ecosystem, the industry can reduce its environmental impact, enhance operational efficiency, and secure its place in a low-carbon future. The examples provided by underscore the potential of technology to revolutionize drilling practices, but they also highlight the need for a concerted effort to overcome the barriers to adoption (Yeap et al., 2020; Edmundson, 2019). As the industry moves forward, it must continue to innovate, collaborate, and invest in the capabilities that will drive sustainability for years to come.

5. Conclusion

This study embarked on a meticulous journey to elucidate the imperative transition from conventional drilling practices to environmentally sustainable ones within the oil and gas industry. The aim was to dissect the multifaceted nature of operational sustainability, scrutinizing the historical, technological, economic, and policy dimensions that underpin this critical shift. A comprehensive literature review systematically addressed the objectives, yielding a tapestry of insights that underscore the urgency and feasibility of sustainable drilling operations.

Key findings from the study reveal that environmental stewardship in drilling activities is not merely a discretionary choice but a pressing necessity. Historical analyses have charted the evolution of drilling technologies, highlighting a trajectory that has increasingly gravitated towards minimizing ecological footprints. The synthesis of literature on sustainable practices has illuminated the intersection of environmental care and economic viability, presenting a compelling case for the adoption of green technologies and methodologies.

The study's recommendations are anchored in the evidence that sustainable drilling practices are not only environmentally sound but also economically prudent. The transition to such practices requires a paradigm shift in both mindset and methodology, underpinned by robust policy frameworks and incentivization strategies. It calls for an industry-wide commitment to innovation, collaboration, and continuous improvement, ensuring that the pursuit of energy resources does not come at the expense of the planet's health.

In conclusion, the findings of this study serve as a clarion call for the oil and gas industry to embrace a future where operational sustainability is the cornerstone of all drilling activities. It is a future that balances the scales between energy production and environmental conservation, ensuring that the industry's legacy is not marred by ecological degradation but characterized by a harmonious coexistence with the natural world. The path forward is clear: sustainable drilling is not just the

right choice but the only choice for a viable future.

References

Abdel, B.A.E.S., Amgad, H.A.R., and Wael, F.A.B., 2022. Evaluating the Financial and Environmental Impacts of Drilling Oil Wells to Achieve Sustainable Development Objectives"(Case study in the fields of Agiba Petroleum Company in–Egypt). Journal of Environmental Science, 51 (4), Pp. 65-104.

Ajayi, O.I., Kehinde, S.A., Akpan, U.J., and Odesa, D.E., 2022. Reducing NPT Amidst Fluctuating Crude Oil Prices: Using Data Analysis to Investigate Well Construction Cost. In SPE Nigeria Annual International Conference and Exhibition (p. D021S009R003). SPE. DOI: 10.2118/212030-ms

Akula, S., Nayak, S.N., Bolar, G., and Managuli, V., 2021. Comparison of conventional drilling and helical milling for hole making in Ti6Al4V titanium alloy under sustainable dry condition. Manufacturing Review, 8, Pp.12. DOI: 10.1051/MFREVIEW/2021010

Al Asy'ari, M.R., Tobing, J., Purba, D., Fadhillah, F.R., Kandou, S.B., and Adityatama, D.W., 2022. Carbon Emissions Reduction in Geothermal Drilling Project: A Preliminary Study. In IOP Conference Series: Earth and Environmental Science, 1014 (1), Pp. 012017. IOP Publishing. https://doi.org/10.1088/1755-1315/1014/1/012017

Al-Kayiem, H.H., Brebbia, C.A., and Zubir, S.S., eds., 2014. Energy and sustainability, 186. WIT Press.

Aprizal, M.F., Juanda, B., Ratnawati, A., and Muin, A., 2022. Indonesian Upstream Oil & Gas Governance for Sustainable Innovation. Jurnal Manajemen dan Organisasi, 13 (1), Pp. 48-60. Journal of Management and Organizational Studies, 13(1). https://doi.org/10.29244/jmo.v13i1.40427

Azunna, C., and Botes, L., 2020. Sustainable Livelihood Capitals and Women's Development in the Eastern State of Nigeria. Administratio Publica, 28 (1), Pp. 82-97.

Azunna, C., and Botes, L., 2020. Sustainable Livelihood Capitals and Women's Development in the Eastern State of Nigeria. Administratio Publica, 28 (1), Pp. 82-97.

Berardi, L., and Giustolisi, O., 2016. Special issue on the battle of background leakage assessment for water networks. Journal of Water Resources Planning and Management, 142 (5), Pp. C2016001. DOI: 10.1061/(ASCE)WR.1943-5452.0000667

Brantley, S.L., 2015. Drinking water while fracking: now and in the future. Ground water, 53 (1), Pp. 21-23.

Choo, J., Noviasta, B. and Hakim, A.I., 2022, August. Establishing Sustainable Oil and Gas Industry: Directional Drilling & Measurement/Logging While Drilling Remote Operations to Achieve Net Zero Carbon Future in Indonesia. In IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition? (p. D012S002R001). SPE. https://doi.org/10.2118/209896-ms

Combs, N.K., Sabins, F., Watters, J., and Watters, L.T., 2017. Preventing Sustained Casing Pressure in Shale Wells. Paper AADE-17-NTCE-114. Amer. Assn. of Drlg. Engrs. Apr. 11-12.

Das, S., 2023. Technology Focus: High Pressure/High Temperature (March 2023). Journal of Petroleum Technology, 75 (03), Pp. 71-72. https://doi.org/10.2118/0323-0071-jpt.

Dow, B., Urbano, S., Rojas Rodriguez, F. and Gupta, C., 2022. Sustainability Metrics for Managed Pressure Drilling. In International Petroleum Technology Conference (p. D021S039R001). IPTC. https://doi.org/10.2523/iptc-21986-ms.

Edmundson, H., 2019. Ten Technologies From the 1980s and 1990s That Made Today's Oil and Gas Industry. Journal of Petroleum Technology, 71 (03), Pp. 44-48. DOI: 10.2118/0319-0044-JPT.

Egba, E.E., Amuda-Kannike, A., Animashaun, O., and Amuda-Kannike, Y., 2023. Oil and Gas Extraction in Nigeria and its Impacts on Environment: Radical Measures to Deep-Seated Challenges of Environmental Sustainability. Asia Pacific Journal of Multidisciplinary Research, 10.31014/aior.1996.02.03.79.

Epelle, E., and Gerogiorgis, D.I., 2020. A review of technological advances and open challenges for oil and gas drilling systems engineering. AIChE Journal, 66 (4), Pp. e16842. https://doi.org/10.1002/aic.16842

Fernandes, G., and Ordonez, R., 2019. Sustainability practices applied in welding process: literature review and case study. Revista dos Trabalhos de Iniciação Científica da UNICAMP, (27), Pp. 1-1.

Ferrari, F., Naselli, R., Brunetti, P., Michelez, J., and Zini, E., 2021, December. Digitalization for Reducing Carbon Footprint in Drilling Operations. In Abu Dhabi International Petroleum Exhibition and Conference (p. D021S033R004). SPE. DOI: 10.2118/207407-ms

Finer, M., Jenkins, C.N., and Powers, B., 2013. Potential of Best Practice to Reduce Impacts from Oil and Gas Projects in the Amazon. PLOS ONE, 8 (5), Pp. e63022. https://doi.org/10.1371/journal.pone.0063022.

Harkouss, R., 2020. Essential Control To Environmental Regulations For Oil And Gas Industry: Spotlight On Drilling Processes In Lebanon. BAU Journal-Science and Technology, 2 (1), Pp.1. 10.54729/2706-784x.1042.

Horvat, D., 2019. Guest Editorial: The Future of Subsea Well Access and Completions. Journal of Petroleum Technology, 71 (08), Pp. 14-15. https://dx.doi.org/10.2118/0819-0014-JPT.

Hu, Y., Sun, J., and Zheng, J., 2021. Comparative analysis of carbon footprint between conventional smallholder operation and innovative largescale farming of urban agriculture in Beijing, China. PeerJ, 9, Pp. e11632. DOI: 10.7717/peerj.11632

Innes, G., Eia, J.T., and Nesse, S., 2022. Case Study: Drill-Cuttings Treatment Alternatives—A Comparative Emissions Assessment. Journal of Petroleum Technology, 74 (02), Pp. 47-50. https://doi.org/10.2118/0222-0047-jpt.

Ivanova, T., 2023. Digital technologies in oil and gas production as a tool to ensure optimal energy efficiency and sustainability. E3S Web of Conferences, 419, Pp. 01007. https://doi.org/10.1051/e3sconf/202341901007

Kareem, W.A., Asa, O.A., and Lawal, M.O., 2015. Resources conservation and waste management practices in construction industry. Oman Chapter of Arabian Journal of Business and Management Review, 34 (2603), Pp. 1-12. DOI: 10.12816/0019071

Kopsidas, O., Giannopoulou, D., and Zarotiadis, G., 2023. Methodological Notes for Cost and Benefit Analysis of Drilling in Eastern Mediterranean. In E3S Web of Conferences, 436, Pp. 04002. EDP Sciences. DOI: 10.1051/e3sconf/202343604002

Kurniadi, S.D., Ryan, A., and Hamidon, Z.R., 2023, September. Strategy for Reducing Environmental Footprint of Hydraulic Fracturing Operations through Engineering Excellence and Operational Efficiency. In SPE International Hydraulic Fracturing Technology Conference and Exhibition. OnePetro. DOI: 10.2118/215686-ms

Kwarto, F., Nurafiah, N., Suharman, H., and Dahlan, M., 2021. Sustainability Reporting in the Upstream Oil and Gas Industry Between Awards and Violations: A Systematic Literature Review, Evidence From Indonesia. DOI: 10.20944/preprints202109.0186.v1

Laari, S., Töyli, J., and Ojala, L., 2018. The effect of a competitive strategy and green supply chain management on the financial and environmental performance of logistics service providers. Business Strategy and the Environment, 27 (7), Pp. 872-883.

Levy, J.K., and Gopalakrishnan, C., 2010. Promoting ecological sustainability and community resilience in the US Gulf Coast after the 2010 Deepwater Horizon oil spill. Journal of Natural Resources Policy Research, 2 (3), Pp. 297-315.

Li, H., Carlson, F., Hanif, A., Zier, J. and Carlson, K., 2023. A Water Stewardship Evaluation Model for Oil and Gas Operators. Energy and Environment Research, 13 (1), Pp. 1-16. DOI: 10.5539/eer.v13n1p16

Lodungi, J.F., Alfred, D.B., Khirulthzam, A.F.M., Adnan, F.F.R.B. and Tellichandran, S., 2016. A review in oil exploration and production waste discharges according to legislative and waste management practices perspective in Malaysia. International Journal of Waste Resources, 7 (1), Pp. 260.

Misopoulos, F., Manthou, V., Michaelides, Z., and Adebayo, A., 2023.

Environmental and Social Sustainability in UK Construction Industry: a Systematic Literature Review. DOI: 10.26417/EJES.V5I1.P100-115

Mohsin, M., Zhu, Q., Naseem, S., Sarfraz, M. and Ivascu, L., 2021. Mining industry impact on environmental sustainability, economic growth, social interaction, and public health: an application of semi-quantitative mathematical approach. Processes, 9 (6), Pp. 972. https://doi.org/10.3390/PR9060972

Perkins, J.L., 2018. Improving the Usefulness of Environmental Information for Decision Making in Organizations. University of California, Santa Barbara.

Quinlan, E., Kuilenburg, R., Williams, T. and Thonhauser, G., 2011. The Impact of Rig Design and Drilling Methods on the Environmental Impact of Drilling Operations. American Association of Drilling Engineers.

Ravasio, C., Pellegrini, G. and Quarto, M., 2023. Development of CO2 efficiency index for evaluating sustainability of microelectrical discharge drilling process. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 237 (5), pp.758-769. https://doi.org/10.1177/09544054221111903

Rodhi, N.N., Anwar, N. and Wiguna, I.P.A., 2017. A review on risk factors in the project of oil and gas industry. IPTEK The Journal for Technology and Science, 28 (3).

Sampson, I.E., Akpabio, J., and Anyadiagwu, C.I., 2020. Economic Analysis of Gas Reinjection for Enhanced Oil Recovery: A Case Study of the Niger Delta. Journal of Engineering Research and Reports, 17 (1), Pp. 48-64. DOI:10.9734/JERR/2020/V17I117181

Samuel, R., Adari, R., and Srinivasan, N., 2022. Engineering and Data-Led Sustainability for Real-Time Monitoring. In IADC/SPE International Drilling Conference and Exhibition. OnePetro. DOI: 10.2118/208796-ms

Siddiquee, M., Shaha, P., and Hasin, A., 2024. Greening the pillars of pharmaceuticals: Sustainable supplier selection in emerging economies. Journal of Future Sustainability, 4 (3), Pp. 159-168. DOI: 10.5267/j.jfs.2024.9.001

Singh, P., and Pant, D., 2018. Waste-To-Waste Management and Resource Conservation And Recycling. Environmental Engineering & Management Journal (EEMJ), 17 (5).

Stern, P.C., Webler, T., and Small, M.J., 2014. Understanding the risks of unconventional shale gas development. Environmental science and technology, 48 (15), Pp. 8287-8288. https://doi.org/10.1021/es502459b.

Umeonaku, L., Aluu, B., Okafor, K. and Atakpa, J., 2023, July. A Sustainable Pathway to Achieving Operational Efficiency While Reducing Carbon Emissions Using Remote Operations and Drilling Automation. In SPE Nigeria Annual International Conference and Exhibition (p. D031S016R002). SPE. DOI: 10.2118/217134-ms

Varanasi, S.S.L., 2023. The Effect and Process Parameters During Conventional Drilling and Abrasive Water Jet Drilling. International Journal of Future Manufacturing and Research, 5 (4). doi: 10.36948/ijfmr.2023.v05i04.4269

Walter, H., 2018. Fossil-Fueled Discourse. Crossing Borders: A Multidisciplinary Journal of Undergraduate Scholarship, 3 (1), Pp. 3. https://doi.org/10.4148/2373-0978.1047

Wells, B., and Hester, T., 2018. Abandoned but Not Forgotten: Improperly Plugged and Orphaned Wells May Pose Serious Concerns for Shale Development. Mich. J. Envtl. & Admin. L., 8, Pp. 115. https://doi.org/10.36640/mjeal.8.1.abandoned.

Wilkinson, P., von Lany, P., and Lane, A., 2014. Environmental stewardship: lessons for European unconventional gas from the United States and Australia. SPE economics & management, 6 (03), Pp. 112-121. https://doi.org/10.2118/167714-MS

World Health Organization. 2019. Guidance for after action review (AAR)(No. WHO/WHE/CPI/2019.4). World Health Organization.

Yeap, W.J., Sidek, S., Naharindra, A., Riyanto, L., Idris, K.N., Bakon, F.L., Ambrose, J.L., Mackie, A., Rajan, S., Sridhar, S., and Wong, K.M., 2020, October. Non-Intrusive Technologies for Prudent Brown Field Redevelopment–An Operator's Experience. In SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition. OnePetro. SPE-196314-MS. DOI: 10.2118/196314-ms.

Zborowski, M., Whitfield, S., Rassenfoss, S., Carpenter, C., and Jacobs, T., 2018. Data, digital energy take center stage at annual conference. Journal of Petroleum Technology, 70 (11), Pp. 55-62. https://doi.org/10.2118/1118-0055-jpt.