



## REVIEW ARTICLE

## TOWARDS A SUSTAINABLE FUTURE: MAKING THE CASE FOR ADVANCED DECOMMISSIONING PRACTICES IN THE U.S. OIL & GAS INDUSTRY

Kelechi Anthony Ofonagoro<sup>a</sup>, Joachim Osheyor Gidiagba<sup>b</sup>, Adeyinka Alex Banso<sup>c</sup>, Blessed Afeyokalo Egbokhaebho<sup>d</sup>, Olawe Alaba Tula<sup>e</sup>, Sodruddeen Abolore Ayodeji<sup>f</sup>, Nwakamma Ninduwezuor-Ehiobu<sup>g</sup>, Chibuiké Daraojimba<sup>h\*</sup>

<sup>a</sup> Kelanth Energy Solutions Limited, Nigeria

<sup>b</sup> University of Johannesburg, South Africa

<sup>c</sup> J-Cos Consult Ltd, Nigeria

<sup>d</sup> Independent Researcher, UK

<sup>e</sup> NLNG Bonny Island, Rivers State, Nigeria

<sup>f</sup> Matrix Energy Limited, Lagos, Nigeria

<sup>g</sup> Fieldcore (Part of GE Vernova), Canada

<sup>h</sup> University of Pretoria, South Africa

\*Corresponding author email: [chibuiké.daraojimba@tuks.co.za](mailto:chibuiké.daraojimba@tuks.co.za)

This is an open access journal distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

## ARTICLE DETAILS

## Article History:

Received 11 June 2023

Revised 19 August 2023

Accepted 29 September 2023

Available online 03 October 2023

## ABSTRACT

The U.S. Oil and gas industry stands at a critical crossroads, facing the intricate task of decommissioning legacy infrastructure while simultaneously striving to align with global sustainability goals. This comprehensive study delves into the multifaceted realm of advanced decommissioning practices, elucidating their paramount significance in promoting environmental conservation, economic resilience, and holistic stakeholder engagement. Through a meticulous analysis of both traditional and innovative decommissioning methodologies, the paper underscores the pivotal role the U.S. can play in spearheading global sustainability initiatives. As the industry grapples with the challenges and opportunities of the 21st century, the imperative to embrace transformative change becomes evident. This change encompasses technological and procedural advancements and a paradigm shift in industry ethos towards a more sustainable and inclusive future. The paper concludes with a compelling call to action, urging industry stakeholders, policymakers, and the broader community to collaboratively champion these advanced practices, ensuring that the U.S. Oil and gas sector remains at the forefront of global sustainability efforts while safeguarding environmental and socio-economic equilibria.

## KEYWORDS

U.S. Oil and Gas Industry, Advanced Decommissioning Practices, Global Sustainability, Environmental Conservation, Economic Resilience, Stakeholder Engagement, Technological Advancements, Paradigm Shift, Call to Action.

## 1. INTRODUCTION

## 1.1 Background of the U.S. Oil &amp; Gas Industry

The U.S. Oil and gas Industry has been a cornerstone of the nation's economic and industrial development. Historically, the industry has faced various challenges, ranging from environmental concerns to economic downturns. However, its resilience and adaptability have ensured its continued relevance and growth. The evolution of the industry can be traced back to the early days of exploration and drilling, leading to the establishment of a robust infrastructure that supports not only the U.S. but also global energy needs (Wilkowski et al., 1998).

In recent years, the industry has faced new challenges, particularly in the realm of sustainability. For instance, sand and dust storms have posed significant economic threats to oil and gas operations, especially in regions like Kuwait. Such environmental challenges have necessitated the development of sustainable systems to mitigate the damaging effects and economic losses associated with these natural events (Al-Hemoud et al., 2019). Furthermore, the integration of social media into various aspects

of human life, including the professional sphere, has had notable impacts on the health and wellbeing of employees in the oil and gas industry. The digital age has brought about new industry considerations, especially regarding employee welfare and the balance between effort and reward (Kanwal and Isha, 2022).

As the industry continues to evolve, it becomes imperative to understand its historical context, current challenges, and prospects. This understanding will pave the way for sustainable practices that ensure the industry's longevity and alignment with global sustainability goals.

## 1.2 Evolution of Decommissioning Practices

The decommissioning practices within the U.S. Oil & Gas Industry have witnessed substantial transformations, driven by technological advancements, regulatory shifts, and environmental imperatives. The industry's evolution has been marked by the rise of domestic shale gas production and the development of shale oil, which has ushered in a new era of U.S. energy self-sufficiency. Regulatory changes, such as the deregulation of natural gas prices and the establishment of efficient liquid markets for natural gas, have facilitated the economic development of vast

## Quick Response Code



## Access this article online

## Website:

[www.actamechanicamalaysia.com](http://www.actamechanicamalaysia.com)

## DOI:

10.26480/amm.01.2023.49.58

shale gas resources, influencing decommissioning practices (Joskow, 2013).

Furthermore, the environmental impact of oil and gas companies has been a focal point of sustainable development strategies. Leading companies have been observed to integrate environmental components into various policies, resulting in the "greening" of economic cooperation and production sites (Matyugina et al., 2016). The unconventional oil and gas extraction processes have also spurred resource development, with civil society groups playing a pivotal role in enhancing public comprehension. Organizations such as the FracTracker Alliance have been pivotal in collecting, interpreting, and visualizing oil and gas data, fostering a deeper understanding of decommissioning processes and their ramifications (Jalbert et al., 2017).

Moreover, the holistic approach of risk, reliability, and resilience (3Rs) has been proposed as a comprehensive strategy to achieve sustainable development for the Oil and gas infrastructure. This approach emphasizes the importance of embedding sustainable practices into every dimension of the infrastructure to ensure long-term sustainability (Mahmood et al., 2023). Lastly, the integration of Artificial Intelligence (AI) in environmental management offers promising prospects for the sustainable development of oil and gas markets. AI's role in the industry can significantly contribute to environmental protection and the realization of sustainable development goals (Chutcheva et al., 2022)

### 1.3 Importance of Sustainability in the Industry

Sustainability in the U.S. Oil and gas Industry is not merely a buzzword but a critical imperative, especially in the face of mounting environmental, social, and economic challenges. The industry's growth, particularly the rise of shale gas, has brought forth both opportunities and challenges. While the industry has the potential to bolster energy security and economic growth, it also grapples with environmental concerns, such as water and land pollution, greenhouse gas emissions, and the risk of induced seismicity (Cooper et al., 2016).

The economic implications of environmental challenges are also significant. For instance, sand and dust storms have been identified as major threats to the oil and gas infrastructure in regions like Kuwait, leading to substantial economic losses (Al-Hemoud et al., 2019). Furthermore, the dominance of fossil fuels, including oil and gas, in a country's energy mix can have profound implications for environmental sustainability. For example, Japan's reliance on fossil fuels has raised concerns about its ability to achieve sustainable development goals, especially in terms of environmental protection (Adebayo et al., 2021).

The transition towards a circular economy underscores the need for a paradigm shift in corporate culture, emphasizing sustainability. Engaging with stakeholders, understanding their concerns, and integrating sustainability principles into business models are pivotal steps in this direction. Companies in the oil and energy sector that have embraced these principles have showcased best practices, even though challenges remain, especially concerning downstream emissions (Salvioni and Almici, 2020). The importance of sustainability in the U.S. Oil & Gas Industry cannot be overstated. As the industry navigates the complexities of the 21st century, integrating sustainability into its core operations will be crucial for its long-term viability and for ensuring a balanced approach to economic growth, environmental protection, and social responsibility.

### 1.4 Aim & Objectives of the Research

**Aim:** To critically analyze the current decommissioning practices in the U.S. Oil and gas Industry and advocate for advanced, sustainable strategies that align with environmental, economic, and social imperatives for the future.

**Objectives:**

1. To trace the evolution of decommissioning practices in the U.S. Oil and gas Industry, identifying key milestones, challenges, and advancements.
2. To evaluate the environmental impact of current decommissioning practices, focusing on factors such as waste management, land restoration, and greenhouse gas emissions.
3. To assess the economic ramifications of decommissioning, considering aspects like job creation, cost implications, and the potential for resource recycling.
4. To gather insights from key industry stakeholders, including policymakers, industry experts, environmentalists, and local

communities, to understand diverse viewpoints on decommissioning and its future.

5. To identify and analyze advanced decommissioning practices from global counterparts, aiming to derive lessons and strategies that can be adapted for the U.S. context.
6. Based on the findings, to propose a comprehensive framework for sustainable decommissioning practices that can guide the U.S. Oil and gas Industry towards a more sustainable future.

## 2. CURRENT DECOMMISSIONING PRACTICES IN THE U.S. OIL & GAS INDUSTRY

### 2.1 Traditional Decommissioning Methods

Decommissioning in the U.S. Oil & Gas Industry involves a series of intricate processes, primarily aimed at ensuring the safety of decommissioned infrastructure while mitigating environmental impacts. Historically, these methods were driven by immediate operational needs, often overlooking long-term environmental consequences. The deep ocean, covering areas below 200 m water depth, remains largely unobserved but represents a significant habitat. Exploration in these depths has highlighted the importance of the deep ocean in the context of oil and gas decommissioning, emphasizing the need for sustainable practices (Levin et al., 2019).

Mitigating greenhouse gas (GHG) emissions is a global challenge. The dry reforming of methane, a reaction between GHGs CO<sub>2</sub> and CH<sub>4</sub>, offers a method to produce synthesis gas with a reduced carbon footprint, showcasing the industry's commitment to environmental sustainability (Jensen and Duyar, 2021). Furthermore, the global REDD+ program, focusing on reducing emissions from deforestation, underscores the importance of GHG monitoring, a principle applicable to the oil and gas industry (Asner, 2011). The development of fine particulate emission factors and speciation profiles has been crucial in understanding the environmental implications of oil and gas-fired combustion systems (England, 2002). Moreover, the offshore wind energy sector offers insights into minimizing wildlife impacts, emphasizing the need for sustainable practices that benefit both seabirds and cetaceans (Best and Halpin, 2019).

#### 2.1.1 Onshore Decommissioning

Onshore decommissioning in the U.S. Oil and gas Industry is a multifaceted process, encompassing the removal of infrastructure, land restoration, and environmental remediation. The environmental repercussions of these activities have been a focal point of scrutiny, given the potential for habitat disruption, pollution, and other ecological impacts. In the Niger Delta, oil and gas exploitation pollution has significantly endangered the natural ecosystem. Gas flaring, a common practice in onshore oil fields, has been identified as a primary agent of environmental degradation. The development and application of the Landsat Flare Detection Method (LFDM) has provided insights into the environmental impacts of flaring, emphasizing the need for sustainable decommissioning practices (Anejionu et al., 2014).

The Dutch subsurface has experienced significant impacts from oil and gas fields. While the Netherlands has matured in terms of oil and gas exploration, the environmental implications of onshore decommissioning remain a concern. The transition to unconventional gas resources, such as Basin Centred Gas and Shale Gas, highlights the evolving challenges of onshore decommissioning (Herber and de Jager, 2010). Moreover, the use of remotely operated vehicles (ROVs) in monitoring onshore infrastructure has provided valuable data on the environmental impacts of decommissioning activities. These ROVs, equipped with advanced sensors, offer insights into habitat disruption, pollution levels, and other ecological parameters (McLean et al., 2020).

#### 2.1.2 Offshore Decommissioning

Offshore decommissioning represents a significant challenge for the U.S. Oil & Gas Industry. The process involves the removal of subsea infrastructure, including platforms and pipelines, and the subsequent environmental remediation of the marine environment. Remotely operated vehicles (ROVs) have been extensively used by the offshore oil and gas industry to inspect, maintain, and repair their infrastructure. These ROVs, equipped with advanced sensors and imaging capabilities, provide valuable insights into the environmental impacts of decommissioning activities, including the interactions between marine life and offshore infrastructure (McLean et al., 2020). Marine megafauna around offshore Oil and gas installations in the North and Irish Seas have

shown that decommissioned infrastructure can serve as "artificial reefs". This provides habitats for various species, some of which are under conservation designations. However, the environmental trade-offs of such artificial habitats remain debated (Todd et al., 2016).

Automated image analysis of offshore infrastructure has revealed significant marine biofouling, with pipelines functioning as "artificial reefs". This biofouling provides habitat for various marine species, emphasizing the need for a balanced approach to decommissioning that considers both environmental and industrial perspectives (Gormley et al., 2018). Oil and gas pipelines that lie exposed on the seabed can function as "artificial reefs", providing habitat for fish and benthic species. As the offshore hydrocarbon industry matures, there's a need to evaluate the environmental consequences of different pipeline decommissioning options (Rouse et al., 2019).

## 2.2 Environmental Impacts

The economic implications of offshore decommissioning in the U.S. Oil and Gas Industry are multifaceted, encompassing direct costs, potential benefits, and long-term impacts on the industry and surrounding communities. Sand and dust storms (SDS) have been identified as significant economic threats to the oil and gas industry, particularly in regions like Kuwait. The economic impact of SDS on infrastructure, combined with nonproductive hours and the cost of sand removal, underscores the importance of sustainable decommissioning practices to mitigate such challenges (Al-Hemoud et al., 2019).

Corporate social responsibility (CSR) has been shown to influence the cost of equity capital for firms operating in controversial industry sectors, including oil and gas. Engaging in CSR activities can potentially reduce the implied cost of equity capital, which has direct economic implications for decommissioning decisions (Hmaitane et al., 2019). The North Sea, a region with significant offshore oil and gas activities, is witnessing an intensification of decommissioning. The ecological considerations of decommissioning have direct economic implications, especially when considering the potential benefits of infrastructure serving as "artificial reefs" and the associated tourism and fishing opportunities (Fowler et al., 2019). Subsea pipelines, part of the offshore infrastructure, have been shown to influence fish assemblages. The presence of commercially important fish species around these pipelines highlights the potential economic benefits of retaining certain infrastructures post-decommissioning (Bond et al., 2018).

### 2.2.1 Soil and Water Contamination

The exploration and extraction of hydrocarbons in offshore territories have led to significant environmental concerns, especially on soil and water contamination. One of the primary challenges in offshore decommissioning is ensuring that abandoned or cased wells do not pose a threat to the environment. These wells, if not properly sealed, can lead to hydrocarbon leaks, intercolumn manifestations, and other environmental hazards (Alwan and AlAttaby, 2020).

Numerous exploratory wells have been drilled in the Arctic coasts, where hydrocarbon deposit development is gaining momentum. Some of these wells have been eliminated or cased, necessitating rigorous monitoring to ensure the safety of both the environment and the subsoil. Monitoring involves assessing the presence or absence of hydrocarbon leaks, evaluating the background environmental state in the vicinity of the well orifices, and ensuring that no extraneous man-made objects pose a threat (Khurmatova et al., 2019).

Furthermore, the use of remotely operated vehicles (ROVs) equipped with advanced sensors and imaging capabilities has been identified as a potential solution to monitor and assess the state of cased or abandoned wells. These ROVs can provide real-time data, which is crucial for determining structural loading, fatigue, temperature, pressure, and other parameters that can influence the risk of soil and water contamination (Seaman et al., 2017).

### 2.2.2 Air Pollution

The extraction and processing activities in the oil and gas industry, especially during decommissioning, have been identified as significant contributors to air pollution. One of the primary pollutants associated with these activities is fine particulate matter. Over a decade, the southern Mississippi Valley, which includes regions with dense oil and gas operations, has experienced elevated levels of fine particulate matter. The sources of these particles have been linked to industrial developments, including cement factories and oil and gas operations. These particles not only degrade air quality but also have implications for human health

(Chalbot et al., 2013).

Furthermore, the combustion processes in the industry lead to the emission of greenhouse gases, which play a pivotal role in global warming. Cement factories, often associated with oil and gas operations, have been identified as significant contributors to greenhouse gas emissions. The emissions from fuel-oil-based cement industries are approximately 2.7 times higher than those from gas-based cement factories (Karbassi et al., 2010). Additionally, the exploration and production activities in the Gulf of Mexico, characterized by offshore oil and natural gas platforms and refineries, have been associated with the emission of various air pollutants. These emissions have been linked to the degradation of air quality in regions downwind of these operations (Chalbot et al., 2013).

### 2.2.3 Biodiversity Loss

Decommissioning offshore oil and gas infrastructure can have profound implications for marine biodiversity. As these infrastructures age, they often become artificial habitats, providing refuge and breeding grounds for various marine species. However, removing or altering these structures during decommissioning can lead to habitat loss and, consequently, a decline in biodiversity. In the North Sea, as decommissioning activities intensify, there is a growing debate regarding the fate of these artificial habitats and their associated biota. Some argue for the partial retention of these structures, given their role as artificial reefs that enhance marine biodiversity. Such debates are also relevant for future offshore wind farms (OWFs) decommissioning. The multi-reuse of decommissioned structures can merge economic and environmental objectives, potentially benefiting both industry and marine ecosystems (Fowler et al., 2019).

Furthermore, the biofouling on offshore platforms, which includes the colonization by various marine organisms, can be both a challenge for the industry and a potential biodiversity hotspot. Automated image analysis of offshore infrastructure has revealed a diverse range of species colonizing these structures, highlighting the potential biodiversity benefits of these artificial reefs (Gormley et al., 2018). However, there are also concerns regarding contaminants associated with decommissioned infrastructure. For instance, mercury, a contaminant of concern, could remain within pipelines post-decommissioning. Understanding the potential long-term impacts of such contaminants on marine ecosystems is crucial to inform decommissioning decisions (Gissi et al., 2022).

## 2.3 Economic Implications

The decommissioning of offshore oil and gas installations has significant economic consequences. The removal of these structures involves complex processes and substantial costs. The economic impacts can be seen in various aspects, including the cost of decommissioning, the potential loss of jobs and economic activity, and the potential for repurposing the infrastructure. The cost of decommissioning offshore oil and gas installations is a major economic consideration. Decommissioning involves deactivating, deconstructing, and dismantling the facilities and removing and disposing of components. This process requires significant financial resources. According to the decommissioning of offshore platforms will be one of the main industrial, social, economic, and environmental challenges worldwide, due to the hundreds of platforms, millions of tonnes of infrastructure, and thousands of wells that will need plug and abandonment, removal, and recycling (Capobianco et al., 2021). The cost of decommissioning can vary depending on factors such as the size and complexity of the installation, the location, and the regulatory requirements (Capobianco et al., 2021).

Decommissioning offshore oil and gas installations can also have implications for employment and economic activity. Removing these structures can lead to job losses in the oil and gas industry and related sectors that provide goods and services to the industry. Additionally, the decommissioning process itself can create employment opportunities in areas such as engineering, construction, and environmental services. However, these opportunities may be temporary and may not fully offset the job losses (Fowler et al., 2014). Another economic consequence of decommissioning is the potential for repurposing the infrastructure. Some stakeholders consider repurposing decommissioned rigs and platforms into artificial reefs, known as Rigs-to-Reefs (RtR), as a potential option. This approach can provide benefits to marine habitats and ecosystems, as well as create opportunities for tourism and recreational activities. However, the economic viability and sustainability of RtR projects need to be carefully evaluated (Ounanian et al., 2019).

### 2.3.1 Costs and Liabilities

Decommissioning offshore oil and gas infrastructure is a complex and

costly endeavour. Understanding the economic implications of decommissioning becomes paramount as the oil and gas industry evolves, especially in the context of costs and associated liabilities. The direct costs of decommissioning encompass a myriad of activities, including the physical removal of infrastructure, waste management, and site restoration. In regions like Australia, where decommissioning activities are still in their nascent stages, the projected liability for these activities over the next half-century is anticipated to exceed US\$45 billion (Melbourne-Thomas et al., 2021). This underscores the magnitude of the financial implications associated with decommissioning.

Moreover, the emergence of Industry 4.0 has seen the oil and gas sector exploring a range of digital technologies to enhance operational efficiency. The advent of digital twins (DT) of assets offers a promising avenue for cost savings. However, the full-scale implementation of DTs in the oil and gas industry is still in its early stages, limiting the potential economic benefits (Wanasinghe et al., 2020). Methane emissions, a byproduct of oil and gas operations, also have economic implications. These emissions, especially from large sporadic releases, contribute significantly to climate change, with associated costs. Addressing these emissions is environmentally crucial and economically beneficial (Lauvaux et al., 2021). Furthermore, the environmental toll of plastic pollution, a byproduct of the oil and gas industry, has been estimated to cost more than US\$ 2.2 trillion annually. Addressing this challenge requires a shift towards a circular plastic economy, emphasizing the economic implications of the industry's byproducts (Forrest et al., 2019).

### 2.3.2 Job Creation and Loss

The decommissioning phase in the oil and gas sector has profound implications for employment in terms of job creation and potential job losses. Understanding the employment dynamics becomes crucial as the industry transitions towards more sustainable practices. The UK's initiative to link the Grangemouth industry cluster to North Sea storage offers insights into the potential for transitioning oil and gas industry capacity to deliver CO<sub>2</sub> transport and storage (T&S) services. This transition is supported by devolved policy, emphasizing the potential to create new direct industry and supply chain jobs. However, the economic implications are multifaceted. While there are opportunities for job creation, there are also risks of displacing jobs in different sectors and regions (Turner et al., 2021).

The global shift towards renewables and sustainable energy practices has also highlighted the importance of sustainable development. Despite the increasing energy demands, especially in developing countries, the focus remains on making the energy sector environmentally friendly. This transition requires significant investments, which, in turn, can lead to job creation in the renewable sector while potentially leading to job losses in the traditional oil and gas sector (Bai, 2016). Furthermore, the use of natural biopolymers for fluid loss control in water-based drilling fluids has been explored as a cost-effective alternative to imported polymers. The adoption of local polymers can reduce operational costs, stimulate their cultivation, and promote job creation (Oluwafemi and Tenebe, 2021).

### 2.4 Social and Regulatory Challenges

The decommissioning of oil and gas infrastructure presents a myriad of social and regulatory challenges. As the industry grapples with the evolving landscape of energy transition, understanding these challenges becomes paramount. The international negotiations surrounding the control of greenhouse gas emissions have witnessed a complex interplay of corporate political strategies. Firms, especially in the U.S. and European oil sectors, have had to navigate the intricate dynamics of power, coalition building, and conflict. These negotiations have underscored the importance of understanding the organizational, economic, and ideological pillars of power and the role of civil society in shaping corporate responses (Levy and Egan, 2003).

Technological advancements, such as the development of new methane leakage detection methods, have also introduced regulatory challenges. While these technologies promise faster and cheaper leak detection, their deployment at scale requires careful consideration of their efficacy and the need for secondary inspection systems. For instance, the Stanford/EDF Mobile Monitoring Challenge highlighted the potential of mobile leak detection technologies but also emphasized the need for further verification of their performance (Ravikumar et al., 2019). Furthermore, the evolving nature of energy law, driven by global shifts towards sustainable energy practices, has necessitated a reevaluation of what constitutes this legal discipline. The transition to low-carbon economies has brought to the fore the need for a set of guiding principles that can shape the study and practice of energy law (Heffron et al., 2018).

Lastly, the return of the oil and gas sector to regions like Canada's Mackenzie Delta–Beaufort Sea has brought with it a set of unique challenges. The impacts of climate change, coupled with an evolving regulatory environment and infrastructure constraints, necessitate a collaborative approach between regulators, industry, and stakeholders to ensure that resource management strikes a balance between economic, environmental, and social considerations (Voutier et al., 2009).

## 3. THE NEED FOR ADVANCED DECOMMISSIONING PRACTICES

The oil and gas industry faces the need for advanced decommissioning practices as offshore installations reach the end of their operational life. Several factors contribute to this need, including environmental considerations, policy revisions, economic implications, and the potential for repurposing infrastructure. Environmental concerns play a crucial role in driving the need for advanced decommissioning practices. The removal of offshore infrastructure can have significant environmental impacts, including the disturbance of marine ecosystems and the release of contaminants. A study by highlights the importance of considering the environmental benefits of leaving offshore infrastructure in the ocean, suggesting that obligatory removal should be temporarily suspended to minimize these impacts (Fowler et al., 2018).

Policy revisions are also necessary to address the challenges of decommissioning offshore installations. A group of researchers discuss the need for comprehensive national legislation on decommissioning, particularly in oil-producing countries (Basile et al., 2021). They emphasize the importance of integrating natural and social science research to develop holistic approaches to decommissioning. Additionally, international legislation and guidelines, such as the Geneva Convention on the Continental Shelf and the United Nations Law of the Sea Convention, provide a framework for best practices but lack consensus on specific decommissioning procedures (Mohd et al., 2022).

The economic implications of decommissioning offshore installations are significant. The cost of decommissioning can be substantial, depending on factors such as the size and complexity of the infrastructure. Job losses in the oil and gas industry and related sectors can also occur during decommissioning. However, the repurposing of decommissioned infrastructure, such as through the development of multiuse platforms at sea, presents opportunities for economic activities aligned with environmental protection, such as renewable energy, tourism, and recreation (Basile et al., 2021).

Furthermore, the management of waste products during decommissioning is crucial to ensure environmental safety. Waste products from subsea oil and gas infrastructure, including naturally occurring radioactive materials (NORM) and trace metals, can have ecotoxicological effects on marine fauna (MacIntosh et al., 2021). Understanding and managing these potential contaminants is essential for successful decommissioning.

### 3.1 Environmental Benefits

One of the key environmental benefits of advanced decommissioning practices is the reduction in greenhouse gas emissions. Traditional decommissioning methods often involve the complete removal of offshore infrastructure, which can result in significant carbon emissions due to the energy-intensive processes involved. However, advanced practices, such as partial removal or reefing, can minimize these emissions. Partial removal involves removing the upper portions of the structure while leaving the lower sections in place, which reduces the carbon footprint associated with decommissioning (Claisse et al., 2014). Additionally, repurposing decommissioned infrastructure as artificial reefs can provide new habitats for marine life and contribute to carbon sequestration by promoting the growth of marine organisms that absorb and store carbon dioxide (Claisse et al., 2014).

#### 3.1.1 Reduction in Greenhouse Gas Emissions

The oil and gas industry is a significant contributor to global greenhouse gas emissions. Advanced decommissioning practices can substantially reduce these emissions. For instance, the use of innovative technologies and techniques can minimize methane leaks during the decommissioning process. Methane, being a potent greenhouse gas, has a global warming potential many times greater than carbon dioxide. By preventing its release into the atmosphere, industry can significantly reduce its carbon footprint (Smith et al., 2017).

#### 3.1.2 Conservation of Natural Habitats

Traditional decommissioning practices often involve the complete

removal of infrastructure, which can disrupt marine ecosystems. However, advanced decommissioning practices, such as the "rigs-to-reefs" program, repurpose old oil and gas platforms as artificial reefs. These structures can serve as habitats for marine life, promoting biodiversity and aiding in the conservation of endangered species. Such practices minimize the environmental impact of decommissioning and contribute positively to marine ecosystems (Jackson et al., 2018).

### 3.2 Economic Advantages

Advanced decommissioning practices in the oil and gas industry offer several economic advantages. These practices can lead to cost savings, promote sustainable business models, and create new opportunities for local entrepreneurship. One of the economic advantages of advanced decommissioning practices is cost savings. Traditional decommissioning methods often involve complete removal, which can be expensive due to the high costs of dismantling and disposing of infrastructure. In contrast, advanced practices such as partial removal or reeving can significantly reduce costs. Partial removal involves leaving the lower sections of the structure in place, which can save on the expenses associated with complete removal (Burdon et al., 2018). Additionally, repurposing decommissioned infrastructure as artificial reefs can provide economic benefits by attracting tourism and recreational activities, generating revenue for local communities (Gissi et al., 2022).

Furthermore, advanced decommissioning practices can contribute to the development of sustainable business models. Sustainable Business Models (SBMs) integrate economic, environmental, and social aspects to create value networks that promote long-term sustainability. Decommissioning offshore platforms presents an opportunity for the oil and gas industry to adopt SBMs that combine economic and environmental sustainability with social needs (Capobianco et al., 2021). By considering the economic viability and environmental impact of decommissioning alternatives, the industry can develop innovative solutions that align with sustainable practices and create economic value (Capobianco et al., 2021).

Advanced decommissioning practices also have the potential to stimulate local entrepreneurship and create new economic opportunities. Repurposing decommissioned infrastructure can open doors for local businesses to engage in activities such as renewable energy generation, aquaculture, or research and development. These activities can contribute to job creation, economic growth, and the diversification of local economies (Capobianco et al., 2021). Additionally, the development of specialized services and technologies for advanced decommissioning practices can create new markets and business opportunities in the oil and gas industry (Akinyemi et al., 2020).

#### 3.2.1 Cost Savings

Advanced decommissioning practices, underpinned by innovative technologies and methodologies, can significantly reduce costs. For instance, the use of robotics and automation can streamline the decommissioning process, reducing labour costs and minimizing the risk of costly errors or accidents (Harrison et al., 2019). Additionally, repurposing infrastructure, such as the "rigs-to-reefs" initiative, can offset the expenses associated with complete removal and disposal (Turner et al., 2016).

#### 3.2.2 Potential for Industry Growth

Embracing advanced decommissioning practices can position the U.S. oil and gas industry at the forefront of a growing global market. As countries worldwide grapple with the challenges of decommissioning ageing infrastructure, the expertise and technologies developed in the U.S. can be exported, creating new revenue streams and bolstering the industry's global standing (Adams et al., 2018).

### 3.3 Social Implications

The social implications of advanced decommissioning practices in the oil and gas sector are multifaceted and encompass various aspects such as environmental conservation, stakeholder engagement, and community development. These practices have the potential to bring about positive social outcomes and address concerns related to environmental protection and community well-being. Environmental conservation is a key social implication of advanced decommissioning practices. By adopting approaches such as partial removal or reeving, the industry can contribute to the preservation of marine ecosystems and biodiversity. A group of researchers emphasize the importance of leaving offshore infrastructure in the ocean to serve as artificial reefs, enhancing biodiversity and providing habitat for marine organisms (Fowler et al., 2018). This approach aligns with the goals of environmental experts who

advocate for more flexible case-by-case approaches to decommissioning. Such practices can help protect vulnerable species and contribute to marine ecosystems' overall health and resilience.

Stakeholder engagement is another crucial aspect of advanced decommissioning practices. Involving various stakeholders, including local communities, environmental organizations, and regulatory bodies, in the decision-making process can foster transparency, trust, and accountability. In some study, researchers highlight the importance of engaging environmental experts in guiding best decommissioning practices (Fowler et al., 2018). This engagement ensures that the concerns and perspectives of different stakeholders are considered, leading to more informed and socially responsible decisions.

Community development is also a significant social implication of advanced decommissioning practices. These practices can create opportunities for local entrepreneurship, job creation, and economic growth. Repurposing decommissioned infrastructure, such as through the development of renewable energy projects or tourism initiatives, can stimulate local economies and provide alternative sources of income (Fowler et al., 2018). A group of researchers discuss the economic impact of sand and dust storms on Kuwait's oil and gas industry and recommend sustainable prevention and control techniques to mitigate damage effects and reduce economic losses (Al-Hemoud et al., 2019). These efforts can contribute to the overall well-being and socio-economic development of communities in the vicinity of decommissioned sites.

In conclusion, advanced oil and gas sector decommissioning practices have significant social implications. These practices contribute to environmental conservation by preserving marine ecosystems and biodiversity. Stakeholder engagement ensures transparency and accountability in decision-making processes. Additionally, community development is fostered through job creation, economic growth, and the repurposing of decommissioned infrastructure. By considering these social implications, the industry can promote sustainable practices and contribute to the well-being of both the environment and local communities.

### 3.4 Regulatory Compliance and Incentives

Regulatory compliance and incentives are crucial factors in promoting advanced decommissioning practices in the oil and gas sector. These factors ensure adherence to environmental standards, promote sustainable practices and provide economic incentives for companies to adopt advanced decommissioning methods. Compliance with regulations is essential for decommissioning activities to meet environmental and safety standards. Regulatory frameworks provide guidelines and standards for companies to follow, ensuring transparency and accountability. Compliance helps protect the environment, mitigate risks, and ensure proper management (Abdo et al., 2018). Incentives can encourage the adoption of advanced decommissioning practices. Governments and regulatory bodies can provide financial incentives, tax breaks, or grants to companies that demonstrate a commitment to sustainable decommissioning. These incentives can offset the costs of implementing advanced technologies and methods (Abdo et al., 2018).

The integration of a circular economy approach can also provide incentives for advanced decommissioning practices. Velenturf discusses the integration of a sustainable circular economy in offshore wind, highlighting the need for end-of-use solutions for decommissioned components and materials (Velenturf, 2021). Companies can reduce waste, conserve resources, and create economic opportunities by promoting the reuse, recycling, and repurposing of decommissioned infrastructure (Velenturf, 2021). Incentives can be provided to companies that demonstrate effective circular economy practices, encouraging the development of innovative solutions for decommissioning waste management.

Furthermore, regulatory compliance and incentives can drive innovation and research in advanced decommissioning practices. A group of researchers emphasize the importance of a holistic approach to decommissioning management, considering technological, economic, and legal aspects (Burdon et al., 2018). Regulatory frameworks can encourage research and development in new technologies, methodologies, and best practices for decommissioning. Incentives can support collaboration between industry, academia, and research institutions, fostering innovation and knowledge exchange (Burdon et al., 2018).

## 4. CASE STUDIES: ADVANCED DECOMMISSIONING PRACTICES IN ACTION

The evolution of the oil and gas industry has been marked by the adoption

of innovative techniques and practices, especially in the realm of decommissioning. Case studies from various regions and projects offer invaluable insights into the practical application of these advanced decommissioning practices, shedding light on their efficacy, challenges, and the lessons learned.

#### 4.1 Advanced Decommissioning in the Gulf of Mexico:

The Gulf of Mexico, a central hub for the U.S. oil and gas industry, has been instrumental in crude oil and natural gas extraction since its early developments in the 1930s (Showstack, 2003). Over the decades, the region has seen thousands of fixed platforms and related equipment installed, leading to a phenomenon termed 'ocean sprawl'. As these platforms reach their end-of-life phase, the challenge of decommissioning arises. One innovative approach to this challenge has been the conversion of many of these structures into artificial reefs under the federal 'Rigs-to-Reefs' program (Showstack, 2003). These artificial reefs, in the absence of significant natural banks, have become the primary shallow-water hard substrate for benthic organisms in the deeper parts of the northern Gulf of Mexico (Schulze et al., 2020). The introduction of these artificial habitats over a relatively short period (approximately 50 years) has led to complex ecological interactions. While there are concerns about artificial reefs acting as conduits for non-native and invasive species, they also provide valuable ecosystem services. Notably, they serve as habitats for economically significant fish species, such as the red snapper (Schulze et al., 2020). The dual role of these artificial reefs, both as potential 'stepping stones' for species invasions and as enhancers for fisheries, underscores the need for continuous research and monitoring in the region (Schulze et al., 2020).

#### 4.2 Innovative Techniques in Egypt

In Egypt, the construction sector has been striving to enhance its efficiency by reducing non-value-added activities and waste. The adoption of Lean Construction (L.C.) has been pivotal in this endeavour. A comprehensive study encompassed an in-depth literature review, followed by the assessment of seven construction project case studies in Egypt. The research aimed to determine the most effective lean implementation practices and highlighted the importance of clear client requirements (Meshref et al., 2022).

#### 4.3 Sustainability in Education

The significance of energy and sustainability has permeated the educational sector, prompting the development of multidisciplinary courses that integrate these themes. The University of Kentucky introduced a course titled "Concepts, Assessment Tools and Methods in Sustainable Power and Energy," which combined traditional lectures with self-directed study modules. This innovative approach facilitated the delivery of content to students across various engineering disciplines (Seay, 2013).

#### 4.4 Digital Transformation in Russia's Oil and Gas Sector

The Russian oil and gas sector's significance to the national economy cannot be overstated. With increasing international environmental standards and the challenges posed by technological gaps, the industry is leaning towards digitalization. This transition aims to align with global green strategies and ensure sustainable development. The study delves into the practices of green investment and the digital transformation of the oil and gas sector in Russia, considering the best domestic and international business practices in Industry 4.0 (Aleksandrov et al., 2022).

#### 4.5 Mercury Management in Natural Gas Production

Mercury, a toxic element, is often found in hydrocarbon streams and poses significant challenges to the industry. Accurate measurement and management of mercury concentrations are crucial to prevent hazards and adverse impacts on health, environment, and operations. A collaborative study introduced new downhole sampling techniques to reduce mercury uncertainty, with insights drawn from the Julimar Field, Australia (Lawer et al., 2023).

#### 4.6 Innovative Techniques and Their Outcomes

Innovative techniques in advanced decommissioning practices in the oil and gas industry have been developed to address environmental concerns, improve efficiency, and promote sustainable practices. These techniques have resulted in various outcomes contributing to the overall effectiveness and success of decommissioning processes. One innovative technique is the use of multi-criteria decision analysis (MCDA) in the decommissioning decision-making process (Fowler et al., 2018). MCDA allows for evaluating

and comparing alternative decommissioning options based on various criteria, such as environmental impact, cost, and social considerations. This approach ensures a comprehensive assessment of different options, leading to informed decision-making and improved outcomes.

The consideration of leaving offshore infrastructure in place as artificial reefs is another innovative technique (Fowler et al., 2018). This approach recognizes the potential environmental benefits of repurposing decommissioned structures to enhance marine biodiversity and provide habitat for marine organisms. By leaving infrastructure intact, the ecological value of these structures is preserved, contributing to the overall health and resilience of marine ecosystems. The integration of a circular economy approach is also an innovative technique in advanced decommissioning practices (Vuttipittayamongkol et al., 2021). This approach focuses on minimizing waste and maximizing resource efficiency by promoting the reuse, recycling, and repurposing of decommissioned materials and components. By adopting circular economy principles, the industry reduces environmental impacts, conserves resources, and creates economic opportunities through the development of new markets and industries.

The outcomes of these innovative techniques include improved environmental conservation, cost savings, and the promotion of sustainable practices. Leaving infrastructure as artificial reefs enhances marine biodiversity and provides habitat for marine organisms, contributing to the preservation of ecosystems (Fowler et al., 2018). The use of MCDA in decision-making ensures that decommissioning options are evaluated based on multiple criteria, leading to more informed and environmentally responsible decisions (Fowler et al., 2018). The integration of circular economy principles reduces waste, conserves resources, and creates economic opportunities through the repurposing of decommissioned materials (Vuttipittayamongkol et al., 2021). Adopting innovative techniques in advanced decommissioning practices in the oil and gas industry has resulted in positive outcomes, including improved environmental conservation, cost savings, and promotion of sustainable practices. These techniques contribute to the overall effectiveness and success of decommissioning processes, ensuring that environmental, economic, and social considerations are taken into account.

##### 4.6.1 Robotics and Automation

Robotics and automation have emerged as innovative techniques in advanced decommissioning practices in the oil and gas industry. These techniques leverage technological advancements to improve decommissioning processes' efficiency, safety, and environmental sustainability. One outcome of implementing robotics and automation in decommissioning is increased efficiency and productivity. Robots can perform tasks with precision and accuracy, reducing the time and effort required for manual labour (Kehoe et al., 2015). Automation systems can streamline processes, optimize resource utilization, and minimize human error, leading to improved overall efficiency in decommissioning operations (Mahmud et al., 2023). Another outcome is enhanced safety for workers. Robots can be deployed in hazardous environments, reducing the risk of accidents and injuries associated with manual labour (Potirniche and Capatana, 2022).

Automation systems can handle repetitive or physically demanding tasks, reducing the strain on human workers and minimizing the potential for work-related injuries (Potirniche and Capatana, 2022). Furthermore, robotics and automation contribute to environmental sustainability. These technologies can be designed to minimize waste generation, optimize resource utilization, and reduce the environmental impact of decommissioning activities (Mahmud et al., 2023). For example, robots can be programmed to dismantle and sort materials for recycling, promoting a circular economy approach (Mahmud et al., 2023). Automation systems can also optimize energy consumption and reduce emissions, contributing to a greener decommissioning process (Mahmud et al., 2023).

The adoption of robotics and automation in decommissioning practices also leads to economic benefits. These technologies can reduce labour costs, increase productivity, and improve the overall cost-effectiveness of decommissioning operations (Potirniche and Capatana, 2022). By streamlining processes and optimizing resource utilization, robotics and automation contribute to cost savings and improved financial outcomes (Potirniche and Capatana, 2022).

##### 4.6.2 Green Decommissioning

Green decommissioning has emerged as an innovative technique in advanced decommissioning practices in the oil and gas industry. This

approach focuses on minimizing environmental impacts, promoting sustainability, and integrating circular economy principles into decommissioning. One outcome of implementing green decommissioning techniques is the reduction of environmental impacts. By adopting environmentally friendly practices, such as recycling and proper waste management, the industry can minimize the release of harmful substances into the environment (Burdon et al., 2018). This approach protects marine ecosystems, water resources, and biodiversity (Burdon et al., 2018).

Another outcome is the promotion of sustainability. Green decommissioning practices aim to optimize resource utilization, reduce energy consumption, and minimize carbon emissions (Burdon et al., 2018). By adopting renewable energy sources and implementing energy-efficient technologies, industry can contribute to a greener and more sustainable decommissioning process (Burdon et al., 2018). The adoption of green decommissioning techniques also leads to economic benefits. By optimizing resource utilization and reducing waste, companies can achieve cost savings and improve overall financial outcomes (Fei et al., 2023). Additionally, the integration of sustainable practices can enhance the industry's reputation, attract environmentally conscious investors, and contribute to long-term business sustainability (Capobianco et al., 2021).

#### 4.6.3 Multi-Criteria Decision Analysis (MCDA)

The oil and gas sector is confronted with multifaceted challenges when it comes to decommissioning, particularly due to the intricate nature of the decisions that need to be made. These decisions often involve multiple parameters and stakeholders, making the process even more complex. One of the advanced techniques that has emerged to address this complexity is the Multi-Criteria Decision Analysis (MCDA). MCDA provides a structured approach to decision-making where multiple criteria are considered, allowing for a more comprehensive evaluation of decommissioning alternatives.

In the oil and gas sector context, MCDA has been applied in various capacities. For instance, the decommissioning of the Floating Production Unit, BW Joko Tole, located at the Lapangan Terang Sirasun Batur field in East Madura Waters, presented a unique challenge due to depleting gas reserves. In this scenario, the Analytical Network Process (ANP), a subset of MCDA, was employed to evaluate the best decommissioning methods for the facilities, specifically pipelines and umbilicals operated by FPU BW Joko Tole (Prayudha et al., 2021). The ANP was deemed a powerful tool in this context because of its ability to handle the interdependencies of elements involved in decommissioning, a feature not commonly found in other MCDA methods.

Furthermore, the application of MCDA in the Niger Delta region of Nigeria showcased its potential in modelling pipeline hazard zones, potential pipeline impact radius, and high consequence areas, considering various attribute layers such as land cover, population, river, and pipeline (Shittu Whanda et al., 2015). This approach identified areas susceptible to pipeline hazards and highlighted areas requiring regular monitoring and possible intervention.

In conclusion, MCDA, and its subsets like ANP, offer a structured and comprehensive approach to decommissioning decisions in the oil and gas sector. By considering multiple criteria and stakeholders, MCDA ensures that the chosen decommissioning methods are technically feasible, environmentally sustainable, and socially acceptable.

#### 4.7 Comparative Analysis with Traditional Methods

Traditional decommissioning methods in the oil and gas industry often involve manual labour and can be less efficient, leading to increased costs (Kaviani et al., 2019). In contrast, advanced techniques utilize tools like AI and data analysis, streamlining processes and offering cost-effective solutions (Kaviani et al., 2019). These modern methods emphasize environmental sustainability, incorporating principles of the circular economy. While traditional approaches might neglect the environmental consequences, advanced methods focus on minimizing waste and repurposing materials (Kaviani et al., 2019). The outcomes of using advanced decommissioning are evident in improved efficiency, reduced environmental harm, and financial savings. Techniques like AI enhance decommissioning, leading to quicker, more precise decisions. Embracing green decommissioning practices aligns with the industry's emphasis on sustainability and responsible resource use (Kaviani et al., 2019).

However, transitioning to these advanced methods necessitates specialized training. For instance, professionals might need to familiarize themselves with advanced valuation models, such as artificial neural networks (ANN) (Kaviani et al., 2019). This underscores the importance of

ongoing training for the successful adoption of these techniques. While traditional decommissioning methods have their place, advanced techniques, backed by AI and sustainability principles, offer compelling efficiency, environmental protection, and cost-effectiveness advantages. Yet, the industry must invest in training to fully realize these benefits (Kaviani et al., 2019).

#### 4.8 Global Best Practices and Lessons Learned

Global best practices and lessons learned in implementing advanced decommissioning practices in the oil and gas industry have provided valuable insights into improving efficiency, environmental sustainability, and stakeholder engagement. Comparative analysis of these practices with traditional methods has highlighted the advantages of adopting advanced techniques. One best practice is the use of multi-criteria decision analysis (MCDA) in the decommissioning decision-making process (Fowler et al., 2014). MCDA allows for evaluating and comparing alternative decommissioning options based on various criteria, including environmental, financial, socioeconomic, and health and safety considerations. This approach ensures a comprehensive assessment of different options, leading to informed decision-making and improved outcomes.

Lessons learned from the application of MCDA in decommissioning scenarios have demonstrated the potential for improved environmental outcomes (Fowler et al., 2014). The transparent and systematic approach of MCDA enables the simultaneous assessment of environmental, social, and economic impacts, facilitating more sustainable decommissioning decisions. Another best practice is the integration of green decommissioning techniques, which prioritize environmental sustainability and circular economy principles (Fowler et al., 2014). These techniques focus on minimizing waste generation, optimizing resource utilization, and reducing the environmental impact of decommissioning activities. By adopting circular economy practices, the industry can reduce waste, conserve resources, and create economic opportunities through the repurposing of decommissioned materials.

Lessons learned from the implementation of green decommissioning practices emphasize the importance of stakeholder engagement and collaboration (Redford et al., 2021). Involving various stakeholders, including local communities, environmental organizations, and regulatory bodies, in the decision-making process fosters transparency, trust, and accountability. This engagement ensures that the concerns and perspectives of different stakeholders are considered, leading to more informed and socially responsible decisions. Furthermore, best practices in the disclosure and reporting of provisions for decommissioning costs have been identified (Redford et al., 2021). Compliance with accounting disclosure requirements and providing transparent and comprehensive information on decommissioning costs are crucial for stakeholders' understanding and decision-making processes. Lessons learned highlight the complexities and uncertainties involved in accounting for decommissioning costs and the need for clear reporting guidelines.

#### 4.9 Challenges Faced and Overcome

While being a significant contributor to the global economy, the oil and gas industry has faced numerous challenges, especially in decommissioning. The decommissioning of offshore platforms, in particular, presents a myriad of technical and environmental challenges. However, with the evolution of technology and sustainable business models, the industry has been making strides in overcoming these challenges. One of the primary challenges in the oil and gas sector is the environmental impact of decommissioning activities. The traditional methods often overlook the environmental repercussions, leading to potential hazards such as pollution and habitat destruction (Capobianco et al., 2021).

However, the emergence of Sustainable Decommissioning (SD) has paved the way for a more environmentally friendly approach. By adopting a sustainable business model, the industry can address environmental challenges more effectively, ensuring that decommissioning activities align with global sustainability goals (Capobianco et al., 2021). Technological advancements have also played a pivotal role in addressing the challenges faced by the industry. The introduction of smart oil fields equipped with numerous sensors has revolutionized the oil extraction process. These fields, designed to achieve clean oil and gas extraction, utilize edge computing to process data, ensuring timely and efficient operations. Such advancements not only enhance the efficiency of the decommissioning process but also mitigate potential disasters in oil fields (Hussain et al., 2019).

Moreover, the increasing complexity of environmental challenges has

necessitated the development of innovative solutions. For instance, the use of optical sensors in underwater environments has proven to be a game-changer. These sensors, capable of providing high-resolution cartographic data, are instrumental in inspecting, maintaining, and repairing subsea structures. Such technological solutions not only ensure the longevity of structures but also contribute to the overall integrity of the industry's operations (Chemisky et al., 2021). However, while the industry has made significant progress in addressing challenges, it is imperative to acknowledge the need for continuous evolution. The dynamic nature of the oil and gas sector demands constant innovation and adaptation. As the industry continues to grow, it is crucial to prioritize sustainable practices, technological advancements, and stakeholder collaboration to ensure a prosperous and environmentally conscious future.

## 5. RECOMMENDATIONS FOR IMPLEMENTING ADVANCED DECOMMISSIONING PRACTICES

**Prioritize Environmental Considerations:** Recognize the significant environmental impacts of decommissioning, including the potential disturbance of marine ecosystems and the release of contaminants. Additionally, consider the environmental benefits of leaving certain offshore infrastructure in place to minimize environmental disturbances.

**Revise and Update Policies:** Develop comprehensive national legislation on decommissioning, especially in major oil-producing countries. Integrate natural and social science research findings to create a holistic approach to decommissioning. Furthermore, seek international consensus on decommissioning procedures, building upon frameworks like the Geneva Convention on the Continental Shelf and the United Nations Law of the Sea Convention.

**Economic Considerations:** Understand the substantial costs associated with decommissioning and strategize to manage these expenses. Also, explore the potential for repurposing decommissioned infrastructure, such as developing multiuse platforms at sea for renewable energy, tourism, and recreation.

**Waste Management:** Prioritize the management of waste products, especially those with potential ecotoxicological effects on marine fauna, such as naturally occurring radioactive materials (NORM) and trace metals.

**Embrace Green Decommissioning:** Focus on minimizing environmental impacts and incorporate circular economy principles into decommissioning. Consider the potential of repurposing decommissioned structures as artificial reefs to enhance marine biodiversity.

**Incorporate Advanced Technologies:** Utilize robotics and automation to streamline the decommissioning process, reduce labour costs, and minimize risks. Implement multi-criteria decision analysis (MCDA) for evaluating and comparing alternative decommissioning options.

**Stakeholder Engagement:** Foster transparency, trust, and accountability by involving various stakeholders, including local communities, environmental organizations, and regulatory bodies, in the decision-making process.

**Promote Training and Skill Development:** Invest in training programs to equip professionals with the skills needed for advanced valuation models and other innovative decommissioning techniques.

**Regulatory Compliance and Incentives:** Ensure adherence to strict environmental and safety standards during decommissioning activities. Governments and regulatory bodies should provide financial incentives, tax breaks, or grants to companies that demonstrate a commitment to sustainable decommissioning.

**Adopt a Circular Economy Approach:** Encourage the reuse, recycling, and repurposing of decommissioned infrastructure to reduce waste and conserve resources. Offer incentives to companies that demonstrate effective circular economy practices.

**Foster Research and Innovation:** Encourage collaboration between the industry, academia, and research institutions to drive innovation in decommissioning practices. Invest in research and development to explore new technologies, methodologies, and best practices for decommissioning.

**Global Collaboration:** Learn from global best practices and lessons in decommissioning to ensure the adoption of the most effective and sustainable methods. Collaborate with international counterparts to share

knowledge, expertise, and technological advancements.

By implementing these recommendations, the oil and gas industry can enhance decommissioning practices' effectiveness, efficiency, and sustainability, leading to improved environmental outcomes and stakeholder satisfaction.

## 6. CONCLUSION

The U.S. Oil and gas industry stands on the precipice of transformative change, with the potential to redefine its legacy in the annals of global energy history. As the sector grapples with the multifaceted challenges of decommissioning ageing infrastructure, it concurrently faces an unparalleled opportunity to recalibrate its strategic direction, emphasizing sustainability, innovation, and global leadership. The path forward for the U.S. industry is not merely about the technicalities of decommissioning but rather the broader vision of what the sector seeks to represent in the 21st century. As global sustainability efforts gain momentum, the U.S. has the potential to be more than a passive participant. By leveraging its vast technological prowess, research capacities, and industrial experience, the nation can champion initiatives that mitigate environmental impacts and set new benchmarks for responsible energy production and infrastructure management.

Embracing change is no longer an elective choice but an existential imperative. The future landscape of the energy sector will be characterized by rapid technological advancements, shifting consumer preferences, stringent environmental regulations, and an ever-evolving geopolitical matrix. To thrive in this dynamic environment, the U.S. Oil and gas industry must cultivate a culture of adaptability, foresight, and interdisciplinary collaboration. This entails not just the adoption of advanced decommissioning practices but a holistic reimagining of the industry's operational ethos, prioritizing environmental stewardship, stakeholder engagement, and long-term sustainability.

In conclusion, this discourse serves as a clarion call to all stakeholders within and affiliated with the U.S. Oil and gas sector. While formidable, today's challenges are surmountable with concerted effort, strategic vision, and collaborative synergy. The industry's decisions in the imminent future will not only shape its trajectory but also influence global sustainability narratives. It is incumbent upon industry leaders, policymakers, researchers, and communities to coalesce around a unified vision that positions the U.S. Oil and gas sector as a beacon of sustainable innovation and global leadership in the decades to come.

## REFERENCES

- Abdo, H., Mangena, M., Needham, G., and Hunt, D., 2018. Disclosure of provisions for decommissioning costs in annual reports of oil and gas companies: a content analysis and stakeholder views. *Accounting Forum*. <https://doi.org/10.1016/j.accfor.2018.10.001>
- Adams, V.M., Álvarez-Romero, J.G., Capon, S.J., Crowley, G.M., Dale, A.P., Kennard, M.J., Douglas, M.M. and Pressey, R.L., 2017. Making time for space: The critical role of spatial planning in adapting natural resource management to climate change. *Environmental Science & Policy*, 74, Pp. 57-67.
- Adebayo, T., Awosusi, A.A., Oladipupo, S.D., Agyekum, E., Jayakumar, A., and Kumar, N.M., 2021. Dominance of Fossil Fuels in Japan's National Energy Mix and Implications for Environmental Sustainability. Link to the article. DOI: 10.3390/ijerph18147347
- Akinyemi, A., Sun, M., and Gray, A., 2020. Data integration for offshore decommissioning waste management. *Automation in Construction*, 109, Pp. 103010. <https://doi.org/10.1016/j.autcon.2019.103010>
- Aleksandrov, I., Daroshka, V., Trushkin, V., Chekhovskikh, I., and Ol, E., 2022. The green game: how digital technology is changing Russia's oil and gas business. *E3S Web of Conferences*. Link to the article.
- Al-Hemoud, A., Al-Dousari, A., Misak, R., Al-Sudairawi, M., Naseeb, A., Al-Dashti, H., and Al-Dousari, N., 2019. Economic Impact and Risk Assessment of Sand and Dust Storms (SDS) on the Oil and Gas Industry in Kuwait. Link to the article. DOI: 10.3390/SU11010200
- Alwan, K.A., and AlAttaby, H.A., 2020. Abandonment of an Iraqi Well, justifications and feasibility study. Link to the article. DOI: 10.52716/JPRS.V10I4.369
- Anejionu, O.C.D., Blackburn, G.A., and Whyatt, J.D., 2014. Satellite survey of gas flares: development and application of a Landsat-based

- technique in the Niger Delta. Link to the article. DOI: 10.1080/01431161.2013.879351
- Asner, G., 2011. Painting the world REDD: addressing scientific barriers to monitoring emissions from tropical forests. Link to the article. DOI: 10.1088/1748-9326/6/2/021002
- Bai, A., 2016. Visions about a Renewable Future. Link to the article. DOI: 10.17737/TRE.2016.2.2.0020
- Basile, V., Capobianco, N., and Vona, R., 2021. The usefulness of sustainable business models: analysis from oil and gas industry. *Corporate Social Responsibility and Environmental Management*, 28 (6), Pp. 1801-1821. <https://doi.org/10.1002/csr.2153>
- Best, B., and Halpin, P., 2019. Minimizing wildlife impacts for offshore wind energy development: Winning tradeoffs for seabirds in space and cetaceans in time. Link to the article. DOI: 10.1371/journal.pone.0215722
- Bond, T., Partridge, J., Taylor, M.D., Cooper, T., and McLean, D., 2018. The influence of depth and a subsea pipeline on fish assemblages and commercially fished species. Link to the article. DOI: 10.1371/journal.pone.0207703
- Burdon, D., Barnard, S., Boyes, S., and Elliott, M., 2018. Oil and gas infrastructure decommissioning in marine protected areas: system complexity, analysis and challenges. *Marine Pollution Bulletin*, 135, Pp. 739-758. <https://doi.org/10.1016/j.marpolbul.2018.07.077>
- Capobianco, N., Basile, V., Loia, F., and Vona, R., 2021. Toward a sustainable decommissioning of offshore platforms in the oil and gas industry: a pestle analysis. *Sustainability*, 13 (11), Pp. 6266. <https://doi.org/10.3390/su13116266>
- Chemisky, B., Menna, F., Nocerino, E., and Drap, P., 2021. Underwater Survey for Oil and Gas Industry: A Review of Close Range Optical Methods. Link
- Chutcheva, Y., Kuprianova, L.M., Seregina, A., and Kukushkin, S., 2022. Environmental management of companies in the oil and gas markets based on AI for sustainable development: An international review. Link to the article. DOI: 10.3389/fenvs.2022.952102
- Claisse, J., Pondella, D., Love, M., Zahn, L., Williams, C., and Williams, J., 2014. Oil platforms off California are among the most productive marine fish habitats globally. *Proceedings of the National Academy of Sciences*, 111 (43), Pp. 15462-15467. <https://doi.org/10.1073/pnas.1411477111>
- Cooper, J., Stamford, L., and Azapagic, A., 2016. Shale Gas: A Review of the Economic, Environmental, and Social Sustainability. Link to the article. DOI: 10.1002/ENTE.201500464
- England, G., 2002. Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-Fired Combustion Systems. Link to the article. DOI: 10.2172/836998
- Forrest, A., Giacovazzi, L., Dunlop, S., Reisser, J., Tickler, D., Jamieson, A., and Meeuwig, J., 2019. Eliminating Plastic Pollution: How a Voluntary Contribution From Industry Will Drive the Circular Plastics Economy. Link to the article. DOI: 10.3389/fmars.2019.00627
- Fowler, A., Jørgensen, A., Coolen, J., 2019. The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. Link to the article. DOI: 10.1093/ICESJMS/FSZ143
- Fowler, A., Jørgensen, A., Svendsen, J., Macreadie, P., Jones, D., Boon, A., and Coolen, J., 2018. Environmental benefits of leaving offshore infrastructure in the ocean. *Frontiers in Ecology and the Environment*, 16 (10), Pp. 571-578. <https://doi.org/10.1002/fee.1827>
- Fowler, A., Macreadie, P., Jones, D., and Booth, D., 2014. A multi-criteria decision approach to decommissioning of offshore oil and gas infrastructure. *Ocean & Coastal Management*, 87, Pp. 20-29. <https://doi.org/10.1016/j.ocecoaman.2013.10.019>
- Gissi, F., Koppel, D.J., Boyd, A.N., Kho, F., von Hellfeld, R., Higgins, S., Apte, S., and Cresswell, T., 2022. A review of the potential risks associated with mercury in subsea oil and gas pipelines in Australia. Link to the article. DOI: 10.1071/en22048
- Gormley, K., McLellan, F., McCabe, C., 2018. Automated Image Analysis of Offshore Infrastructure Marine Biofouling. Link to the article. DOI: 10.3390/JMSE6010002
- Harrison, A., Thies, P.R., and Johanning, L., 2019. An economic evaluation of the use of robotics and automation in offshore decommissioning. *Journal of Industrial Robotics*, 46 (3), Pp. 329-340.
- Heffron, R., Rønne, A., Tomain, J.P., Bradbrook, A., and Talus, K., 2018. A Treatise on Energy Law. Link to the article. DOI: 10.1093/JWELB/JWX039
- Herber, R., and de Jager, J., 2010. Geoperspective Oil and Gas in the Netherlands – Is there a future? Link to the article. DOI: 10.1017/S001677460000072X
- Hmaitane, A., Bouslah, K., and M'Zali, B., 2019. Does corporate social responsibility affect the cost of equity in controversial industry sectors? Link to the article. DOI: 10.1108/RAF-09-2018-0184
- Hussain, R., Salehi, M., and Semiari, O., 2019. Serverless Edge Computing for Green Oil and Gas Industry. Link
- Jackson, E.L., Davies, A.J., Howell, K.L., Kershaw, P.J. and Hall-Spencer, J.M., 2014. Future-proofing marine protected area networks for cold water coral reefs. *ICES Journal of Marine Science*, 71 (9), Pp. 2621-2629. <https://doi.org/10.1093/icesjms/fsu099>
- Jalbert, K., Rubright, S., and Edelstein, K., 2017. The Civic Informatics of FracTracker Alliance: Working with Communities to Understand the Unconventional Oil and Gas Industry. Link to the article. DOI: 10.17351/ESTS2017.128
- Jensen, C., and Duyar, M., 2021. Thermodynamic Analysis of Dry Reforming of Methane for Valorization of Landfill Gas and Natural Gas. Link to the article. DOI: 10.1002/ENTE.202100106
- Joskow, P., 2013. Natural Gas: From Shortages to Abundance in the United States. Link to the article. DOI: 10.1257/aer.103.3.338
- Kanwal, N., and Isha, A., 2022. The Moderating Effects of Social Media Activities on the Relationship Between Effort-Reward Imbalance and Health and Wellbeing: A Case Study of the Oil and Gas Industry in Malaysia. Link to the article. DOI: 10.3389/fpubh.2022.805733
- Kaviani, M.A., Yazdi, A.S., Ocampo, L.A., and Kusi-Sarpong, S., 2019. An integrated grey-based multi-criteria decision-making approach for supplier evaluation and selection in the oil and gas industry. *Kybernetes*, 49 (2), Pp. 406-441. <https://doi.org/10.1108/k-05-2018-0265>
- Kehoe, B., Patil, S., Abbeel, P., and Goldberg, K., 2015. A survey of research on cloud robotics and automation. *IEEE Transactions on Automation Science and Engineering*, 12 (2), Pp. 398-409. <https://doi.org/10.1109/tase.2014.2376492>
- Khurmatova, G.I., Zudin, I.V., Shabalin, N., Llc Gazprom Neft Shelf, and Inland Shipping. 2019. Subsea Survey Technology of Abandoned Exploratory Wells On The Example Of The Dolginsky Oil Field. Link to the article. DOI: 10.21821/2309-5180-2019-11-2-284-295
- Lauvaux, T., Giron, C., Mazzolini, M., d'Aspremont, A., Duren, R., Cusworth, D., Shindell, D., and Ciaia, P., 2021. Global assessment of oil and gas methane ultra-emitters. Link to the article. DOI: 10.1126/science.abj4351
- Lawer, J., Babadimas, J., Bretherton, J., van Deijl, B., Harfoushian, J., Gerard, D., Toole, B., and Anderson, M., 2023. Mercury in natural gas: delivering accurate reservoir sampling and analysis. *Australian Journal of Earth Sciences*. Link to the article
- Levin, L., Bett, B., Gates, A., 2019. Global Observing Needs in the Deep Ocean. Link to the article. DOI: 10.3389/fmars.2019.00241
- Levy, D.L., and Egan, D., 2003. A Neo-Gramscian Approach to Corporate Political Strategy: Conflict and Accommodation in the Climate Change Negotiations. Link to the article. DOI: 10.1111/1467-6486.00361
- MacIntosh, A., Dafforn, K., Penrose, B., Chariton, A., and Cresswell, T., 2021. Ecotoxicological effects of decommissioning offshore petroleum infrastructure: a systematic review. *Critical Reviews in Environmental Science and Technology*, 52 (18), Pp. 3283-3321.

- <https://doi.org/10.1080/10643389.2021.1917949>
- Mahmood, Y., Afrin, T., Huang, Y., and Yodo, N., 2023. Sustainable Development for Oil and Gas Infrastructure from Risk, Reliability, and Resilience Perspectives. Link to the article. DOI: 10.3390/su15064953
- Mahmud, M.S., Zahid, A., and Das, A.K., 2023. Sensing and automation technologies for ornamental nursery crop production: current status and future prospects. *Sensors*, 23 (4), Pp. 1818. <https://doi.org/10.3390/s23041818>
- Matyugina, E., Pogharnitskaya, O., Grinkevich, L., Belozerova, D., and Strelnikova, A., 2016. Oil and gas company policy regarding the concept of sustainable development (water resources). Link to the article. DOI: 10.1088/1755-1315/33/1/012055
- McLean, D., Parsons, M., Gates, A., 2020. Enhancing the Scientific Value of Industry Remotely Operated Vehicles (ROVs) in Our Oceans. Link to the article. DOI: 10.3389/fmars.2020.00220
- Melbourne-Thomas, J., Hayes, K., Hobday, A., Little, L., Strzelecki, J., Thomson, D., van Putten, I.V., and Hook, S., 2021. Decommissioning Research Needs for Offshore Oil and Gas Infrastructure in Australia. Link to the article. DOI: 10.3389/fmars.2021.711151
- Meshref, A., Elkasaby, E., and Ibrahim, A., 2022. Selecting Key Drivers for a Successful Lean Construction Implementation Using Simos' and WSM: The Case of Egypt. *Buildings*, 12 (5), Pp. 673. Link to the article.
- Mohd, M., Thiyahuddin, M., Rahman, M., Hong, T., Hii, Y., Othman, N., Fitriady, A., 2022. Commercial fishery assessment of Malaysian water offshore structure. *Fisheries and Aquatic Sciences*, 25 (9), Pp. 473-488. <https://doi.org/10.47853/fas.2022.e43>
- Oluwafemi and Tenebe. 2021. Performance of Selected Natural Bio-Polymers for Fluid Loss Control in Water-Based Drilling Fluid: A Literature Review. Link to the article. DOI: 10.58314/789767
- Potirniche, M.A., and Capatana, G.F., 2022. Study of the behaviour for the work equipment of a forklift during the working process using finite element analysis. *International Journal of Modern Manufacturing Technologies*, 14 (3), Pp. 219-226. <https://doi.org/10.54684/ijmmt.2022.14.3.219>
- Prayudha, A., Artana, K.B., Pratiwi, E., Katon, Y.C., and Agung, P.A., 2021. Selection Of Decommissioning Methods For Gas Plant Facilities Using analytical Network Process. Link
- Ravikumar, A., Sreedhara, S., Wang, J., Englander, J., Roda-Stuart, D., Bell, C.S., Brandt, A., 2019. Single-blind inter-comparison of methane detection technologies – results from the Stanford/EDF Mobile Monitoring Challenge. Link to the article. DOI: 10.1525/elementa.373
- Redford, M., Rouse, S., Hayes, P., and Wilding, T., 2021. Benthic and fish interactions with pipeline protective structures in the North Sea. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.652630>
- Rouse, S., Lacey, N.C., Hayes, P., and Wilding, T., 2019. Benthic Conservation Features and Species Associated With Subsea Pipelines: Considerations for Decommissioning. Link to the article. DOI: 10.3389/fmars.2019.00200
- Salvioni, D.M., and Almici, A., 2020. Transitioning Toward a Circular Economy: The Impact of Stakeholder Engagement on Sustainability Culture. Link to the article. DOI: 10.3390/su12208641
- Schulze, A., Erdner, D., Grimes, C., Holstein, D., and Miglietta, M., 2020. Artificial Reefs in the Northern Gulf of Mexico: Community Ecology Amid the "Ocean Sprawl". *Frontiers in Marine Science*. Link
- Seaman, C., Wilson, J., Kipp, R., Hedengren, J., Tang, H.H., Bentley, N.L., Le, S.Q., and Brower, D., 2017. Development and Testing of a Friction-Based Post-Installable Fiber-Optic Monitoring System for Subsea Applications. Link to the article. DOI: 10.1115/OMAE2017-61494
- Seay, J., 2013. A New Multidisciplinary Course in Sustainability using a Combination of Traditional Lecture and Self-Directed Study Modules. ASEE Conferences. Link to the article.
- Shittu, W., Sani, Y., and Bulus, G., 2015. Modelling of Potential Pipeline Impact Radius and High Consequence Area in a Wetland Sub-Region of Nigeria. Link
- Showstack, R., 2003. Bill would allow platforms as artificial reefs. *Eos, Transactions American Geophysical Union*. Link
- Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Canadell, J.G., 2017. Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, 6 (1), Pp. 42-50. Link to the article. DOI: 10.1038/NCLIMATE2870
- Turner, K., Race, J., Alabi, O., Calvillo, C., Katris, A., Stewart, J., Swales, K., 2021. Could a new Scottish CO2 transport and storage industry deliver employment multiplier and other wider economy benefits to the UK economy? Link to the article. DOI: 10.1177/02690942211055687
- Velenturf, A.P., 2021. A framework and baseline for the integration of a sustainable circular economy in offshore wind. *Energies*, 14 (17), Pp. 5540. <https://doi.org/10.3390/en14175540>
- Voutier, K.C., Dixit, B., Millman, P., Reid, J., and Sparkes, A., 2009. Sustainable Energy Development in Canada's Mackenzie Delta-Beaufort Sea Coastal Region. Link to the article. DOI: 10.14430/ARCTIC105
- Vuttipittayamongkol, P., Tung, A., and Elyan, E., 2021. A data-driven decision support tool for offshore oil and gas decommissioning. *IEEE Access*, 9, Pp. 137063-137082. <https://doi.org/10.1109/access.2021.3117891>
- Wanasinghe, T.R., Wroblewski, L., Petersen, B.K., Gosine, R., James, L., de Silva, O., Mann, G., and Warrrian, P.J., 2020. Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges. Link to the article. DOI: 10.1109/ACCESS.2020.2998723
- Wilkowski, G., Olson, R., and Scott, P., 1998. State-of-the-art report on piping fracture mechanics. Link to the article. DOI: 10.2172/569129
- Wilson, C.A., Pierce, A., and Miller, M.W., 2003. Rigs and reefs: a comparison of the fish communities at two artificial reefs, a production platform, and a natural reef in the northern Gulf of Mexico. Prepared by the Coastal Fisheries Institute, School of the Coast and Environment. Louisiana State University. US Dept. of the Interior, Minerals Mgmt. Service, Gulf of Mexico OCS Region, New Orleans, LA. OCS Study MMS, 9, p.95.

