Magna Scientia
Open access publication

Magna Scientia Advanced Research and Reviews

eISSN: 2582-9394

Cross Ref DOI: 10.30574/msarr

Journal homepage: https://magnascientiapub.com/journals/msarr/

Magna Scientia Advanced Research and Reviews (MSARR)

(Review Article)

Check for updates

Hydrogen production and utilization in oil and gas facilities

Williams Ozowe [1,*], Augusta Heavens Ikevuje [2], Adindu Donatus Ogbu [3] and Andrew Emuobosa Esiri [4]

[1] *Independent Researcher; USA.*
[2] *Independent Researcher, Houston Texas, USA.*
[3] *Schlumberger (SLB) Port Harcourt, Nigeria and Mexico.*
[4] *Independent Researcher, Houston Texas, USA.*

Magna Scientia Advanced Research and Reviews, 2023, 08(02), 251–263

Publication history: Received on 21 June 2023; revised on 24 August 2023; accepted on 27 August 2023

Article DOI: https://doi.org/10.30574/msarr.2023.8.2.0112

Abstract

The transition to hydrogen as a cleaner energy carrier within oil and gas facilities presents a promising opportunity to reduce carbon emissions and promote sustainable energy practices. This review investigates the potential for hydrogen production and utilization in oil and gas operations, focusing on hydrogen-powered equipment and fuel cells as alternatives to conventional carbon-intensive technologies. The research explores the feasibility of integrating hydrogen into oil and gas processes, examining its role in decarbonizing operations through the replacement of diesel generators, compressors, and other machinery. Hydrogen production methods such as steam methane reforming (SMR) with carbon capture and storage (CCS) and electrolysis using renewable energy are analyzed to assess their viability in large-scale industrial applications. Additionally, the use of hydrogen fuel cells is explored as a means to provide reliable, low-emission energy for various on-site applications, including power generation, transportation, and heating. The review highlights both the technical and economic challenges associated with hydrogen adoption in oil and gas facilities, such as infrastructure development, hydrogen storage, and distribution. However, it also emphasizes the long-term benefits, including reduced greenhouse gas emissions, compliance with global environmental regulations, and improved operational efficiency. By investigating hydrogen's role as a cleaner energy carrier, this research contributes to the ongoing discourse on transitioning the oil and gas industry towards more sustainable and environmentally friendly practices.

Keywords: Hydrogen Production; Oil and Gas; Utilization; Review

1. Introduction

As the world increasingly confronts the pressing challenge of climate change, the quest for sustainable energy solutions has taken on a critical role (Ahmad *et al*., 2021). Among various alternatives, hydrogen has emerged as a key player in the transition toward a low-carbon economy. Recognized for its potential as a clean energy carrier, hydrogen offers a promising pathway to decarbonize several industrial sectors, particularly the oil and gas industry, which is notorious for its significant carbon emissions (Guilbert and Vitale, 2021). This explores the pivotal role of hydrogen in reducing emissions within the oil and gas sector, its importance in global energy transition efforts, and the investigation into hydrogen production and utilization to replace carbon-intensive technologies. Hydrogen is the most abundant element in the universe and can be utilized in various forms, including gas, liquid, and solid, making it a versatile energy carrier (Zhang *et al*., 2021). When used as a fuel, hydrogen produces only water vapor as a byproduct, thus offering a zero-emission alternative to conventional fossil fuels. The potential for hydrogen to replace carbon-intensive fuels has gained momentum as countries set ambitious targets for emissions reduction. The adoption of hydrogen technologies can significantly mitigate greenhouse gas emissions associated with fossil fuel combustion, thereby contributing to global climate goals. The oil and gas industry is a significant contributor to global carbon emissions, accounting for a

* Corresponding author: Williams Ozowe

substantial percentage of total greenhouse gas emissions (Nong *et al*., 2021). As regulatory frameworks and societal expectations shift toward sustainability, the industry faces mounting pressure to reduce its carbon footprint. Hydrogen can play a transformative role in this regard. By integrating hydrogen into various operational processes, including refining, chemical production, and transportation, the oil and gas sector can significantly lower its emissions (Zou *et al*., 2022). For instance, hydrogen can be employed in refining processes to replace carbon-heavy hydrogen sources derived from natural gas (gray hydrogen) with green hydrogen produced from renewable energy sources. This shift not only enhances the sustainability of oil and gas operations but also aligns with broader decarbonization strategies, enabling the sector to meet regulatory standards and consumer expectations for cleaner energy solutions (Blazquez *et al*., 2020; Green *et al*., 2022).

The global energy transition is characterized by a shift away from fossil fuels toward renewable energy sources. Hydrogen serves as a crucial link in this transition, facilitating the integration of intermittent renewable energy sources, such as wind and solar, into the energy system (Furfari and Clerici, 2021). Hydrogen can be produced through electrolysis powered by renewable energy, providing a storage solution for excess energy during periods of low demand or high generation. This versatility positions hydrogen as an essential component of a resilient and flexible energy infrastructure, capable of supporting the transition to a sustainable energy future. Moreover, hydrogen can help address challenges related to energy security and supply chain resilience (Carlson *et al*., 2023). By diversifying energy sources and enabling cross-sectoral applications, hydrogen enhances energy independence and reduces vulnerability to fossil fuel supply fluctuations. As countries strive to achieve their climate commitments, hydrogen emerges not only as a clean energy carrier but also as a strategic asset in achieving energy security.

Given the significant potential of hydrogen, this review aims to investigate the production and utilization of hydrogen in oil and gas facilities to replace carbon-intensive technologies. This includes examining various hydrogen production methods, such as electrolysis, steam methane reforming with carbon capture and storage (CCS), and biomass gasification. Additionally, the review will explore the infrastructure required for hydrogen storage, distribution, and utilization within existing oil and gas facilities. By focusing on these aspects, the research seeks to identify pathways for integrating hydrogen technologies in oil and gas operations, thereby facilitating the sector's transition toward sustainability. Ultimately, the findings will contribute to a deeper understanding of how hydrogen can be harnessed to reduce emissions, enhance energy security, and support global efforts to combat climate change.

2. Hydrogen Production Technologies

Hydrogen is widely recognized as a clean energy carrier, with various production technologies available to harness its potential for reducing emissions across multiple sectors, including oil and gas (Noussan *et al*., 2002). This explores three key hydrogen production technologies: Steam Methane Reforming (SMR), Electrolysis, and other emerging methods, highlighting their current applications, environmental impacts, and the technological advancements driving efficiency.

Steam Methane Reforming (SMR) is the dominant method of hydrogen production in the oil and gas industry, accounting for approximately 95% of global hydrogen production. (Khan *et al*., 2021) In this process, natural gas, primarily composed of methane (CH_4), is reacted with steam at high temperatures (700–1,000°C) in the presence of a catalyst. While SMR is cost-effective and well-established, it results in significant CO_2 emissions, which contribute to climate change. Current estimates suggest that for every ton of hydrogen produced via SMR, approximately 9–12 tons of CO_2 are released into the atmosphere. To mitigate this environmental impact, the implementation of carbon capture and storage (CCS) technologies is essential (Mikunda *et al*., 2021). CCS involves capturing CO_2 emissions from SMR and storing them underground or repurposing them for industrial applications, thereby reducing the overall carbon footprint of hydrogen production.

Electrolysis is an alternative method for producing hydrogen, particularly green hydrogen, which uses renewable energy sources to split water (H_2O) into hydrogen and oxygen. The electrolysis process involves passing an electric current through water, causing it to dissociate into its constituent elements (Chatenet *et al*., 2022). The primary advantage of electrolysis is its potential to produce hydrogen without associated CO_2 emissions when powered by renewable energy sources such as wind, solar, or hydroelectric power. As the global energy landscape increasingly shifts toward renewables, the potential for on-site hydrogen production becomes more viable. For instance, wind turbines or solar panels can be integrated into hydrogen production facilities, allowing for local, decentralized hydrogen generation. This on-site production not only reduces transportation costs but also enhances energy security and resilience by utilizing locally available renewable resources.

Despite its advantages, electrolysis faces challenges related to efficiency and cost. Current electrolysis technologies have conversion efficiencies ranging from 60% to 80%, and the high capital costs associated with electrolyzers can hinder widespread adoption. Nevertheless, ongoing research and technological advancements aim to improve the efficiency of electrolysis systems, reduce costs, and develop innovative designs such as proton exchange membrane (PEM) and solid oxide electrolyzers (SOE) (Sebbahi *et al*., 2022).

Beyond SMR and electrolysis, several emerging hydrogen production technologies show promise for enhancing efficiency and sustainability. One such method is methane pyrolysis, which involves the thermal decomposition of methane into hydrogen and solid carbon without producing CO_2 emissions. Methane pyrolysis offers the potential for low-emission hydrogen production while generating solid carbon that can be used in various industrial applications, such as materials manufacturing (Patlolla *et al*., 2023). Solid oxide electrolysis (SOE) is another innovative approach that utilizes high-temperature electrolysis to enhance efficiency. SOE operates at temperatures between 700°C and 1,000°C, significantly increasing the reaction kinetics and potentially achieving higher efficiencies (up to 90%). By utilizing waste heat from industrial processes, SOE can further improve overall energy efficiency and reduce operational costs. Hydrogen production technologies play a critical role in the transition to a low-carbon economy, especially within the oil and gas sector. Steam Methane Reforming remains the primary method of hydrogen production, yet its CO_2 emissions necessitate the integration of carbon capture and storage technologies (Antonini *et al*., 2020). Electrolysis, particularly when powered by renewable energy, presents a sustainable alternative for producing green hydrogen, with significant potential for on-site production. Emerging technologies, such as methane pyrolysis and solid oxide electrolysis, offer additional pathways for efficient and low-emission hydrogen production. As advancements continue to be made in these technologies, hydrogen stands poised to become a cornerstone of global efforts to achieve a sustainable and decarbonized energy future.

2.1. Hydrogen Utilization in Oil and Gas Operations

As the oil and gas industry strives to reduce its carbon footprint and transition toward sustainable practices, hydrogen emerges as a pivotal resource for enhancing operational efficiency and minimizing environmental impact (Dincer and Aydin, 2023). This examines the utilization of hydrogen in oil and gas operations, focusing on hydrogen-powered equipment, hydrogen fuel cells, and hydrogen's role in Enhanced Oil Recovery (EOR).

One of the most promising applications of hydrogen in the oil and gas sector is the replacement of conventional diesel-powered equipment with hydrogen-powered alternatives. Hydrogen-powered drills, compressors, and other machinery can significantly reduce greenhouse gas emissions and particulate matter associated with fossil fuel combustion (Rolo *et al*., 2023). These alternatives are particularly appealing as the industry seeks to align with global climate goals while maintaining productivity and operational effectiveness. Several pilot projects have demonstrated the viability of hydrogen-powered equipment in real-world scenarios. For instance, a notable project involved the adaptation of drilling rigs to operate on hydrogen fuel, showcasing the technology's capability to deliver performance comparable to traditional diesel engines. Such pilot projects not only validate the technical feasibility of hydrogen-powered equipment but also pave the way for broader implementation across the industry. By transitioning to hydrogen-powered machinery, operators can reduce dependency on fossil fuels, thereby mitigating operational costs and improving environmental performance (Kovač *et al*., 2021).

Hydrogen fuel cells represent another significant advancement in hydrogen utilization within oil and gas operations. These electrochemical devices convert hydrogen and oxygen into electricity, producing only water vapor as a byproduct. Fuel cells can provide a reliable power source for offshore and onshore rigs, offering a cleaner alternative to traditional energy sources such as gas turbines and diesel engines. When compared to conventional power generation methods, hydrogen fuel cells exhibit several advantages, including higher efficiency, lower emissions, and reduced noise levels (Aminudin *et al*., 2023). For example, hydrogen fuel cells can achieve efficiency rates of up to 60%, surpassing the typical 30-40% efficiency of gas turbines. Furthermore, the modular nature of fuel cell systems allows for flexibility in installation and scalability, making them suitable for various operational scales within the industry. Several companies have begun adopting hydrogen fuel cells in their operations, demonstrating the technology's potential to enhance energy sustainability. Noteworthy examples include the use of fuel cells to power critical systems on offshore platforms, where reliability and environmental considerations are paramount. These initiatives not only showcase the practical application of fuel cells in challenging environments but also serve as a model for future energy solutions in the sector.

Enhanced Oil Recovery (EOR) techniques are essential for maximizing extraction from existing oil fields (Cheraghi *et al*., 2021). Hydrogen presents a clean and efficient alternative for EOR processes. Traditionally, methods such as steam injection or carbon dioxide flooding have been employed, often resulting in significant emissions. Utilizing hydrogen in EOR can help to reduce these emissions while maintaining or even enhancing recovery rates. The incorporation of hydrogen in EOR processes offers several environmental and operational benefits. For instance, hydrogen can lower the viscosity of crude oil, improving its flow and facilitating extraction. Moreover, the use of hydrogen reduces reliance on carbon-intensive methods, contributing to overall emissions reduction in the oil and gas sector. Preliminary studies indicate that hydrogen-based EOR can lead to improved recovery efficiency while simultaneously decreasing greenhouse gas emissions associated with traditional recovery methods. Additionally, the operational benefits of hydrogen-based EOR extend to enhanced reservoir management and economic performance (Sekar *et al*., 2023). By adopting hydrogen as a tool for EOR, oil and gas operators can improve the sustainability of their operations while simultaneously securing their economic viability in a transitioning energy landscape.

The utilization of hydrogen in oil and gas operations offers a promising pathway toward sustainable practices and reduced environmental impact. The transition from conventional diesel-powered equipment to hydrogen-powered alternatives enhances operational efficiency and aligns with global climate objectives. Hydrogen fuel cells provide a reliable and clean power source, demonstrating superior efficiency compared to traditional energy generation methods (Rasaki *et al*., 2021). Furthermore, the application of hydrogen in Enhanced Oil Recovery processes not only enhances extraction rates but also reduces emissions associated with conventional methods. As the industry continues to evolve, the adoption of hydrogen technologies will be crucial in fostering a sustainable energy future for the oil and gas sector.

2.2. Infrastructure and Technical Challenges

As the oil and gas industry increasingly incorporates hydrogen as a clean energy carrier, various infrastructure and technical challenges must be addressed to facilitate its effective utilization (Ishaq *et al*., 2022). Key challenges include hydrogen storage and transportation, retrofitting existing infrastructure, and ensuring safety in handling hydrogen in oil and gas environments.

Hydrogen storage and transportation present significant challenges due to the unique properties of hydrogen. Hydrogen is the lightest and smallest molecule, which makes it highly diffusive and prone to leakage. Storing hydrogen in oil and gas facilities involves choosing appropriate methods that balance safety, efficiency, and economic feasibility (Tashie-Lewis and Nnabuife, 2021). Common storage methods include compressed gas, liquid hydrogen, and metal hydrides. Compressed hydrogen gas is typically stored in high-pressure tanks, which can handle pressures up to 700 bar. However, this method poses challenges regarding tank integrity and potential leakage. Liquid hydrogen, stored at cryogenic temperatures (-253°C), offers a higher energy density but requires sophisticated insulation and safety measures to prevent boil-off and maintain temperature stability. Recent technological advancements aim to improve hydrogen storage solutions, such as solid-state storage technologies that utilize metal hydrides, which can absorb and release hydrogen at lower pressures and temperatures. Furthermore, developing specialized pipelines and infrastructure for hydrogen transportation is crucial to ensure safe and efficient distribution. Hydrogen can be transported via dedicated pipelines, repurposed natural gas pipelines, or in chemical carriers (Tsiklios *et al*., 2022). Each method presents unique challenges, including material compatibility and leakage prevention, necessitating ongoing research and development.

Integrating hydrogen into existing oil and gas infrastructure poses compatibility challenges. Many facilities, including refineries and processing plants, were not originally designed to handle hydrogen. Hydrogen embrittlement, a phenomenon where hydrogen molecules diffuse into metals and cause material degradation, can compromise the structural integrity of pipelines and equipment (Ohaeri *et al*., 2018). The retrofitting process can be technically complex and costly, requiring careful assessment of existing infrastructure to determine its suitability for hydrogen use. This may involve material upgrades, such as replacing carbon steel with more resistant alloys, and implementing modifications to existing systems to accommodate hydrogen's unique properties. The costs associated with retrofitting facilities can be substantial, creating a barrier to widespread adoption. However, strategic investments in retrofitting can enhance the long-term viability of existing infrastructure and facilitate the transition to hydrogen as a key energy carrier.

Safety is a paramount concern when handling and utilizing hydrogen in oil and gas environments. Hydrogen is flammable and can form explosive mixtures with air, necessitating stringent safety protocols throughout its lifecycle. (Moretto and Quong, 2022) Addressing safety concerns involves implementing comprehensive risk management strategies that encompass hydrogen storage, transportation, and utilization. Best practices for mitigating risks associated with hydrogen include regular inspections and maintenance of storage tanks and pipelines, employing leak detection systems, and training personnel on safe handling procedures. Additionally, establishing clear safety regulations and standards for hydrogen use in oil and gas facilities is essential to promote safe operations and public confidence. Emerging technologies, such as advanced monitoring systems utilizing sensors and artificial intelligence, offer the potential to enhance safety by providing real-time data on hydrogen storage and transportation conditions. This can help identify potential leaks and hazards before they escalate, allowing for timely intervention and response.

The integration of hydrogen into oil and gas operations presents several infrastructure and technical challenges that must be addressed to unlock its full potential as a clean energy carrier. Effective hydrogen storage and transportation require advancements in storage technologies and the development of specialized pipelines and infrastructure (Yang *et al*., 2023). Retrofitting existing facilities to accommodate hydrogen necessitates careful consideration of compatibility and associated costs. Finally, prioritizing safety through robust risk management strategies and best practices is essential for fostering a secure environment for hydrogen use in the oil and gas industry. By addressing these challenges, the industry can pave the way for a sustainable energy future, leveraging hydrogen's benefits while mitigating potential risks.

2.3. Economic Feasibility of Hydrogen Integration

As the global energy landscape evolves towards sustainability, the integration of hydrogen as a clean energy carrier in the oil and gas industry has garnered significant attention. This explores the economic feasibility of hydrogen integration, focusing on cost-benefit analysis, incentives and financial support, and the market potential for hydrogen within the oil and gas sector.

The economic feasibility of hydrogen production hinges on a comprehensive cost-benefit analysis comparing traditional energy sources with hydrogen (Bigestans *et al*., 2023). Currently, hydrogen production costs can vary significantly depending on the method employed, with steam methane reforming (SMR) being the most prevalent method. However, this method is carbon-intensive, resulting in significant greenhouse gas emissions and potential future regulatory costs. In contrast, green hydrogen production methods, such as electrolysis powered by renewable energy sources, are gaining traction despite higher initial costs. Over time, the long-term economic benefits of adopting hydrogen technologies become increasingly apparent. One major advantage is the reduction of carbon taxes and compliance costs associated with emissions regulations. As governments worldwide tighten regulations on carbon emissions, industries reliant on fossil fuels face escalating costs. By integrating hydrogen technologies, companies can mitigate these risks, potentially saving millions in carbon compliance costs and leveraging the economic benefits of a cleaner operational footprint. Additionally, the decreasing costs of renewable energy, coupled with technological advancements in hydrogen production, suggest a promising trajectory for hydrogen's economic competitiveness (Li *et al*., 2023).

To facilitate hydrogen adoption, various government incentives, tax breaks, and supportive policy frameworks are essential. Many countries have recognized the importance of hydrogen in achieving climate goals and have introduced subsidies to promote research and development in hydrogen technologies. For instance, tax incentives can reduce the upfront costs associated with hydrogen infrastructure investments, encouraging companies to transition away from fossil fuels. Public-private partnerships (PPPs) play a crucial role in driving investment in hydrogen technologies. By collaborating with private sector entities, governments can leverage resources, expertise, and innovation to accelerate the development and deployment of hydrogen solutions (De Blasio *et al*., 2020). Successful examples of PPPs in hydrogen integration include joint ventures for building hydrogen production facilities and shared investments in transportation infrastructure. Such collaborations not only foster innovation but also reduce financial risks associated with large-scale hydrogen projects, thereby enhancing their economic viability.

The market potential for hydrogen in oil and gas operations is substantial, driven by increasing demand for cleaner energy solutions. Hydrogen is poised to play a critical role in various applications within the sector, including hydrogen-powered equipment, fuel cells for power generation, and Enhanced Oil Recovery (EOR) processes. As oil and gas companies seek to enhance their sustainability profiles, the demand for hydrogen is expected to grow significantly. Moreover, the opportunities for hydrogen extend beyond the oil and gas sector, positioning it as a viable commercial energy source in various industries. Sectors such as transportation, manufacturing, and chemical production are increasingly exploring hydrogen's potential as a clean fuel alternative (Sazali, 2020). For instance, hydrogen fuel cells are being adopted in heavy-duty transportation, such as trucks and trains, while hydrogen is utilized in the production of ammonia for fertilizers. This diversification of hydrogen applications further enhances its market potential and economic viability.

The economic feasibility of hydrogen integration in the oil and gas industry is increasingly supported by a favorable cost-benefit analysis, robust government incentives, and significant market potential. While initial production costs may be higher compared to traditional energy sources, the long-term benefits of reducing carbon taxes and compliance costs position hydrogen as a strategically advantageous choice. Furthermore, the role of public-private partnerships in driving investment and innovation cannot be overstated, as these collaborations facilitate the necessary advancements in hydrogen technologies (Karpyn *et al*., 2021). As the market for hydrogen continues to expand, it holds the promise of transforming the oil and gas sector while contributing to global sustainability goals, ultimately paving the way for a cleaner and more resilient energy future.

2.4. Environmental Impact and Decarbonization Potential

As the world grapples with the urgent need to address climate change, hydrogen has emerged as a promising low-carbon energy carrier with significant potential to mitigate environmental impacts and facilitate the decarbonization of the oil and gas industry (Bugaje *et al*., 2022). This explores hydrogen's role in reducing greenhouse gas emissions and its contribution to achieving net-zero targets, as well as its ability to lower methane and CO2 emissions during oil production.

Hydrogen is regarded as a low-carbon energy carrier because its combustion produces only water vapor, making it a cleaner alternative to traditional fossil fuels. In hydrogen-powered operations, such as fuel cells and hydrogen-powered equipment, the reliance on hydrogen significantly reduces greenhouse gas emissions compared to conventional processes that emit carbon dioxide (CO2) and other pollutants (Hosseini and Butler, 2020). For example, when hydrogen is used as a fuel in drilling operations, it can replace diesel and natural gas, leading to a substantial decrease in emissions associated with these fossil fuels. The integration of hydrogen into the oil and gas sector is instrumental in helping companies achieve their net-zero targets. Many oil and gas companies have set ambitious goals to reduce their carbon footprints in response to regulatory pressures and societal expectations. By adopting hydrogen technologies, these companies can transition to cleaner operations while still meeting energy demands. Furthermore, hydrogen can serve as a bridging technology, allowing the oil and gas industry to maintain its operational viability while progressively reducing its reliance on carbon-intensive energy sources. This transitional role is crucial for achieving long-term decarbonization goals without sacrificing energy security.

Hydrogen's potential to reduce methane and CO2 emissions is particularly relevant in the context of oil production, where methane leaks pose significant environmental challenges. Methane, a potent greenhouse gas with a much higher global warming potential than CO2 over a short time frame, is often released during oil extraction and transportation (Balcombe *et al*., 2018). By integrating hydrogen into oil production processes, companies can implement measures to detect and reduce methane leaks more effectively. Research indicates that using hydrogen in production operations can facilitate the conversion of methane into hydrogen and CO2 through a process known as steam methane reforming (SMR), albeit with carbon capture and storage (CCS) technologies in place. This process can significantly reduce the net greenhouse gas emissions associated with traditional methane production, particularly if the hydrogen is derived from renewable sources. Moreover, hydrogen's role in enhancing oil recovery techniques can lead to lower overall emissions by improving extraction efficiency while minimizing methane venting (Asadi *et al*., 2021). Several case studies highlight the environmental benefits of hydrogen integration in oil and gas operations. For instance, pilot projects utilizing hydrogen-powered equipment have demonstrated significant reductions in CO2 emissions during drilling operations. In one project, the implementation of hydrogen fuel cells for powering drilling rigs resulted in an over 50% reduction in greenhouse gas emissions compared to diesel-powered alternatives. These case studies underscore hydrogen's effectiveness in reducing the environmental footprint of oil and gas operations, showcasing its potential to drive sustainable practices within the industry.

Hydrogen presents a compelling solution for addressing the environmental impact of the oil and gas industry while facilitating the transition toward decarbonization. As a low-carbon energy carrier, hydrogen significantly reduces greenhouse gas emissions from hydrogen-powered operations, contributing to the achievement of net-zero targets. Furthermore, hydrogen's ability to mitigate methane and CO2 emissions in oil production through innovative technologies and practices enhances its environmental benefits. The successful implementation of hydrogen in pilot projects illustrates its potential to transform the oil and gas sector into a more sustainable and environmentally responsible industry (Litvinenko *et al*., 2020). As the global energy landscape continues to evolve, embracing hydrogen as a key component of decarbonization strategies will be essential for achieving climate goals and promoting a cleaner, more sustainable future.

2.5. Regulatory and Policy Considerations

As the global community intensifies its efforts to combat climate change, regulatory and policy frameworks have become essential in driving the adoption of hydrogen technologies in the oil and gas industry (Guo *et al*., 2023). In recent years, various international and regional initiatives have emerged to promote hydrogen as a clean energy source, particularly in sectors like oil and gas. One prominent example is the European Union's Hydrogen Strategy, introduced in 2020, which aims to support the large-scale deployment of hydrogen technologies across member states. This strategy outlines a roadmap for developing a competitive hydrogen market, focusing on green hydrogen production and its integration into existing energy systems. The EU has allocated significant funding for research and innovation in hydrogen technologies, encouraging member states to invest in infrastructure and facilitate the transition to a hydrogen economy. In the United States, similar efforts are underway through the Hydrogen Economy initiative, which emphasizes the development and deployment of hydrogen technologies to reduce greenhouse gas emissions and promote energy security. The U.S. Department of Energy (DOE) has established programs to support research and development in hydrogen production, storage, and utilization. Furthermore, federal policies aim to encourage public-private partnerships to stimulate investment in hydrogen-related projects, particularly in the oil and gas sector. Other regions, including Japan and South Korea, have also implemented national hydrogen strategies that emphasize the development of hydrogen infrastructure and its application in energy-intensive industries (Pingkuo and Xue, 2022). These comprehensive policies reflect a global recognition of hydrogen's potential as a key player in the transition to a sustainable energy future.

The adoption of hydrogen technologies in the oil and gas industry aligns closely with global climate agreements and emission reduction targets. The Paris Agreement, for example, emphasizes the importance of transitioning to low-carbon energy sources to limit global warming to well below 2 degrees Celsius. Hydrogen, particularly when produced from renewable sources, plays a critical role in achieving these goals by significantly reducing greenhouse gas emissions from fossil fuel operations. As nations implement stricter emission standards and carbon pricing mechanisms, the adoption of hydrogen technologies becomes increasingly attractive. Regulatory frameworks that mandate emission reductions create a favorable environment for companies to explore hydrogen as a viable alternative to traditional fossil fuels (Cheng and Lee, 2022). By integrating hydrogen into their operations, oil and gas companies can enhance their compliance with emission reduction targets, avoiding potential penalties and contributing to their sustainability commitments.

To facilitate the transition to hydrogen, governments worldwide are offering various incentives to encourage early adopters of hydrogen technologies in the oil and gas industry. These incentives may include tax credits, grants, and subsidies aimed at offsetting the initial costs associated with hydrogen production, infrastructure development, and technology deployment (Saha *et al*., 2021). For example, some countries provide financial support for research and development projects that focus on innovative hydrogen solutions, allowing companies to invest in cutting-edge technologies that enhance efficiency and reduce emissions. Moreover, governments may implement regulatory measures that prioritize hydrogen technologies in permitting processes, enabling quicker approvals for hydrogen-related projects. These supportive policies can significantly reduce barriers to entry for companies looking to integrate hydrogen into their operations, fostering a more conducive environment for innovation and investment.

The regulatory and policy landscape surrounding hydrogen technologies is pivotal in facilitating their adoption within the oil and gas industry. Global and regional hydrogen policies, such as the EU Hydrogen Strategy and U.S. Hydrogen Economy efforts, underscore the commitment to promoting hydrogen as a clean energy source. Compliance with emission reduction targets aligns hydrogen adoption with international climate agreements, incentivizing companies to transition toward cleaner operations (Rissman *et al*., 2002). Additionally, the incentives for early adopters play a crucial role in reducing barriers to entry and fostering innovation. As governments continue to develop and refine these policies, the potential for hydrogen to transform the oil and gas sector into a more sustainable and environmentally responsible industry becomes increasingly attainable.

2.6. Case Studies of Hydrogen Utilization in Oil and Gas Facilities

As the oil and gas industry seeks to reduce its carbon footprint and embrace cleaner energy alternatives, hydrogen has emerged as a viable solution (Lau *et al*., 2021). This examines notable case studies of hydrogen utilization in oil and gas facilities, focusing on initiatives by Equinor, Shell, and various North American oil fields.

Equinor, a Norwegian energy company, has been at the forefront of hydrogen production and utilization initiatives, driven by its commitment to sustainability and reducing greenhouse gas emissions. One of the notable projects is the HyNor initiative, which aims to establish a hydrogen production and distribution infrastructure in Norway. This project involves the production of hydrogen through electrolysis powered by renewable energy sources, with the goal of supplying hydrogen for transportation and industrial applications. In addition to HyNor, Equinor is also involved in the Northern Lights project, which focuses on carbon capture and storage (CCS) while leveraging hydrogen as an integral part of its energy transition strategy. This project aims to capture CO2 emissions from industrial processes and store them underground, reducing overall emissions. Despite its successes, Equinor has faced challenges in integrating hydrogen into its existing operations (Damman *et al*., 2020). These include the high costs associated with hydrogen production, the need for infrastructure development, and regulatory hurdles. Nevertheless, the company remains committed to overcoming these challenges and expanding its hydrogen portfolio, illustrating the potential of hydrogen as a clean energy carrier in the oil and gas sector.

Shell has also been actively exploring hydrogen fuel cells, particularly in offshore operations. One significant project is the Hydrogen Fuel Cell Demonstration on the Jack/St. Malo platform in the Gulf of Mexico. This initiative aims to integrate hydrogen fuel cells to provide power for offshore operations, thereby reducing reliance on traditional fossil fuels. The initial results from this project have been promising, demonstrating the potential for hydrogen fuel cells to provide reliable power while significantly lowering emissions. Shell's approach emphasizes the scalability of hydrogen technologies, as the company plans to expand the use of hydrogen fuel cells to other offshore facilities (Hassan *et al*., 2023). The incorporation of hydrogen fuel cells not only enhances energy efficiency but also positions Shell as a leader in the transition toward a low-carbon energy future.

In North America, several oil fields are beginning to adopt hydrogen-based technologies, particularly for enhanced oil recovery (EOR) processes. One notable case review is the implementation of hydrogen-powered equipment in the Permian Basin, where operators have begun utilizing hydrogen as a means to improve oil extraction efficiency. By injecting hydrogen into reservoirs, companies have reported enhanced oil recovery rates, leading to increased production and reduced greenhouse gas emissions compared to traditional EOR methods (Kang *et al*., 2022). The adoption of hydrogen-powered equipment, such as hydrogen-fueled compressors and drills, has demonstrated tangible benefits in terms of operational efficiency and environmental impact. Companies operating in the Permian Basin have noted reductions in carbon emissions and operational costs, showcasing the effectiveness of hydrogen as a clean alternative to conventional fossil fuel technologies. Moreover, pilot projects in other North American oil fields have illustrated similar benefits (Hill *et al*., 2020). For instance, operators have reported improved methane leak detection and reduction when hydrogen is integrated into their processes. These advancements not only contribute to emission reductions but also enhance the overall sustainability of oil field operations.

The case studies of hydrogen utilization in oil and gas facilities, exemplified by Equinor's hydrogen initiatives, Shell's hydrogen fuel cell projects, and the adoption of hydrogen-based technologies in North American oil fields, highlight the transformative potential of hydrogen in the industry. As companies navigate the challenges of integrating hydrogen into their operations, the successes observed in these case studies serve as a testament to the viability of hydrogen as a clean energy solution. Moving forward, the continued investment in hydrogen technologies and the sharing of best practices will be crucial for driving further adoption and facilitating the oil and gas sector's transition toward a more sustainable future.

2.7. Future Trends and Opportunities in Hydrogen Adoption

As the global energy landscape evolves, hydrogen is poised to play a critical role in achieving sustainable energy goals. The shift toward renewable energy-driven hydrogen production is gaining momentum, reflecting a broader commitment to sustainability. Green hydrogen, produced through the electrolysis of water using renewable energy sources such as wind, solar, or hydroelectric power, offers a carbon-neutral alternative to conventional hydrogen production methods (Kakoulaki *et al*., 2021). As technology advances and the cost of renewable energy continues to decline, the viability of large-scale green hydrogen production becomes increasingly feasible. In the context of oil and gas operations, green hydrogen presents a unique opportunity to decarbonize processes traditionally reliant on fossil fuels. For instance, oil refineries can integrate green hydrogen into their operations to replace natural gas in hydrogen production for hydrocracking, thereby significantly reducing carbon emissions. Furthermore, as oil and gas companies seek to align with global climate targets, investing in green hydrogen production becomes a strategic imperative, enabling these companies to transition toward more sustainable practices.

Innovations in hydrogen technology are crucial to enhancing its adoption in the oil and gas sector. Emerging technologies, such as hydrogen-based combustion engines and advancements in fuel cell technology, are paving the way for more efficient and versatile applications of hydrogen. Hydrogen combustion engines, which can power vehicles and equipment without producing greenhouse gases, represent a significant advancement, offering an alternative to traditional fossil fuel-powered systems (Yu *et al*., 2023). Additionally, hydrogen fuel cells continue to evolve, with improvements in efficiency, durability, and cost-effectiveness. These advancements are making fuel cells an attractive option for various applications, including stationary power generation and transportation. Moreover, the integration of artificial intelligence (AI) and automation in hydrogen utilization presents substantial opportunities for optimization in oil and gas facilities. AI algorithms can analyze operational data to enhance hydrogen production efficiency, streamline supply chains, and optimize consumption patterns. Automation can facilitate real-time monitoring and control of hydrogen systems, ensuring safety and maximizing output (Abdelghany *et al*., 2023). Collectively, these technological advancements are set to transform how hydrogen is produced and utilized across the industry.

Hydrogen's integration into the broader energy ecosystem is a pivotal trend in the transition to a low-carbon future. As a versatile energy carrier, hydrogen can complement renewable energy sources, providing storage solutions for excess electricity generated during peak production periods. This flexibility allows for better management of energy supply and demand, enhancing grid stability and reliability. Furthermore, there are significant opportunities for collaboration between oil and gas companies and renewable energy providers. By leveraging existing infrastructure, expertise, and investment, partnerships can accelerate the development of hydrogen projects (Harichandan and Kar, 2023). For instance, oil and gas companies can play a vital role in the transportation and storage of hydrogen, utilizing their extensive pipeline networks and storage facilities. Conversely, renewable energy providers can supply the clean energy necessary for green hydrogen production, creating a symbiotic relationship that fosters innovation and efficiency.

The future of hydrogen adoption in the oil and gas industry is marked by promising trends and opportunities. The expansion of green hydrogen production, coupled with advancements in technology and strategic collaborations, positions hydrogen as a cornerstone of the energy transition. As the industry continues to evolve, embracing hydrogen solutions will not only enhance sustainability but also drive economic growth and innovation. By investing in hydrogen now, oil and gas companies can secure their place in a decarbonized future, aligning with global climate goals while meeting the energy demands of tomorrow (Telegina and Chapaikin, 2022).

2.8. Challenges and Barriers to Widespread Hydrogen Use

One of the primary barriers to hydrogen adoption is the high initial cost associated with hydrogen production and the necessary retrofitting of existing infrastructure (Gordon *et al*., 2023). Currently, most hydrogen is produced through conventional methods such as steam methane reforming (SMR), which, while cost-effective, emits significant greenhouse gases. Transitioning to greener hydrogen production methods, such as electrolysis powered by renewable energy, entails substantial capital investment in new technologies and infrastructure. Additionally, retrofitting existing oil and gas facilities to accommodate hydrogen usage involves not only financial outlays but also technical complexities that can deter investment. Another significant challenge is the technical difficulties associated with storing, transporting, and utilizing hydrogen, especially in offshore environments. Hydrogen has a low energy density by volume, making it less efficient to store and transport compared to conventional fuels. High pressures or cryogenic temperatures are often required for storage, necessitating specialized equipment that can be costly to develop and implement. Furthermore, hydrogen's small molecular size increases the risk of leakage and necessitates stringent safety measures, complicating its deployment in offshore operations where harsh environmental conditions can exacerbate these risks (Van Hoecke *et al*., 2021).

Navigating the complex regulatory frameworks surrounding hydrogen adoption is another substantial barrier. Regulatory bodies across different regions and countries have varying standards and guidelines for hydrogen production, storage, and transportation (Dawood *et al*., 2020). This fragmentation can create uncertainty for companies considering investments in hydrogen technologies, as they may face differing compliance requirements, thereby slowing down the pace of adoption. Moreover, safety concerns in deploying hydrogen technologies in hazardous oil and gas environments cannot be overlooked. Hydrogen is highly flammable and can pose significant risks if not managed properly. The existing safety protocols for traditional hydrocarbons may not be directly applicable to hydrogen, necessitating the development of new guidelines and training programs for personnel working with hydrogen technologies. Addressing these safety concerns is crucial for fostering confidence among stakeholders and ensuring the safe integration of hydrogen into oil and gas operations.

To overcome these barriers, technological innovations are essential for lowering costs and improving the handling of hydrogen. For instance, advancements in hydrogen production methods, such as more efficient electrolyzers or innovative carbon capture technologies, can reduce the overall cost of green hydrogen production. Additionally, research into new materials for hydrogen storage and transport can enhance safety and efficiency, making it easier to integrate hydrogen into existing infrastructure (Abdalla *et al*., 2018). Policy support is equally critical in facilitating the transition to a hydrogen economy. Governments can implement incentives, such as tax credits or subsidies, to encourage investment in hydrogen technologies and infrastructure. Creating clear and consistent regulatory frameworks can also streamline the adoption process, providing companies with the confidence to invest in hydrogen solutions. Public-private partnerships can further enhance innovation and investment, fostering collaboration between industry stakeholders and government agencies.

While hydrogen holds immense potential as a clean energy carrier, several challenges and barriers must be addressed to enable its widespread adoption, particularly in the oil and gas sector (Nazir *et al*., 2020). By focusing on overcoming technical and economic barriers, navigating regulatory complexities, and fostering innovation and policy support, stakeholders can pave the way for a successful transition to a hydrogen-based energy future. Embracing these solutions will not only advance sustainability goals but also ensure that hydrogen becomes a viable and integral component of the global energy landscape (Zakaria *et al*., 2023).

3. Conclusion

In summary, hydrogen emerges as a pivotal solution for decarbonizing oil and gas operations, offering a pathway to significantly reduce greenhouse gas emissions and enhance sustainability. Its potential to serve as a clean energy carrier is evidenced by its applications in various sectors, including hydrogen-powered equipment and fuel cells, which can effectively replace conventional fossil fuel-based technologies. The feasibility of hydrogen production and utilization in oil and gas facilities is increasingly supported by advancements in production technologies, such as electrolysis and methane pyrolysis, along with ongoing pilot projects that demonstrate successful integration.

The outlook for hydrogen in the oil and gas industry is promising, as it is poised to become a core component of sustainable energy practices. With the global energy transition gaining momentum, hydrogen can play a vital role in achieving net-zero targets and fostering a more resilient energy ecosystem. However, realizing this potential requires continued investment in infrastructure and technology, alongside supportive policy frameworks that incentivize hydrogen adoption. As the industry navigates the complexities of hydrogen integration, collaboration between stakeholders, including oil and gas companies and renewable energy providers, will be essential.

The path to a hydrogen-powered future necessitates a concerted effort to overcome existing barriers and harness the opportunities presented by this versatile energy carrier. By prioritizing technological advancement and aligning investment strategies with long-term sustainability goals, the oil and gas sector can leverage hydrogen to not only decarbonize its operations but also contribute to the broader efforts of combating climate change and fostering a sustainable energy landscape.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abdalla, A.M., Hossain, S., Nisfindy, O.B., Azad, A.T., Dawood, M. and Azad, A.K., 2018. Hydrogen production, storage, transportation and key challenges with applications: A review. *Energy conversion and management*, *165*, pp.602-627.

[2] Abdelghany, M.B., Mariani, V., Liuzza, D., Natale, O.R. and Glielmo, L., 2023. A unified control platform and architecture for the integration of wind-hydrogen systems into the grid. *IEEE Transactions on Automation Science and Engineering*.

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

[4] Aminudin, M.A., Kamarudin, S.K., Lim, B.H., Majilan, E.H., Masdar, M.S. and Shaari, N., 2023. An overview: Current progress on hydrogen fuel cell vehicles. *International Journal of Hydrogen Energy*, *48*(11), pp.4371-4388.

[5] Antonini, C., Treyer, K., Streb, A., van der Spek, M., Bauer, C. and Mazzotti, M., 2020. Hydrogen production from natural gas and biomethane with carbon capture and storage–A techno-environmental analysis. *Sustainable Energy & Fuels*, *4*(6), pp.2967-2986.

[6] Asadi, J., Yazdani, E., Dehaghani, Y.H. and Kazempoor, P., 2021. Technical evaluation and optimization of a flare gas recovery system for improving energy efficiency and reducing emissions. *Energy conversion and management*, *236*, p.114076.

[7] Balcombe, P., Speirs, J.F., Brandon, N.P. and Hawkes, A.D., 2018. Methane emissions: choosing the right climate metric and time horizon. *Environmental Science: Processes & Impacts*, *20*(10), pp.1323-1339.

[8] Bigestans, D., Cardin, M.A. and Kazantzis, N., 2023. Economic performance evaluation of flexible centralised and decentralised blue hydrogen production systems design under uncertainty. *Applied Energy*, *352*, p.121944.

[9] Blazquez, J., Dale, S., Jefferiss, P., Heffron, R.J., Herbertson, J., West, R. and Hegland, J., 2020. Decarbonization pathways for oil and gas. In *Oxford Energy Forum* (Vol. 121, pp. 1-40).

[10] Bugaje, A.A.B., Dioha, M.O., Abraham-Dukuma, M.C. and Wakil, M., 2022. Rethinking the position of natural gas in a low-carbon energy transition. *Energy Research & Social Science*, *90*, p.102604.

[11] Carlson, E.L., Pickford, K. and Nyga-Łukaszewska, H., 2023. Green hydrogen and an evolving concept of energy security: Challenges and comparisons. *Renewable Energy*, *219*, p.119410.

[12] Chatenet, M., Pollet, B.G., Dekel, D.R., Dionigi, F., Deseure, J., Millet, P., Braatz, R.D., Bazant, M.Z., Eikerling, M., Staffell, I. and Balcombe, P., 2022. Water electrolysis: from textbook knowledge to the latest scientific strategies and industrial developments. *Chemical society reviews*, *51*(11), pp.4583-4762.

[13] Cheng, W. and Lee, S., 2022. How green are the national hydrogen strategies?. *Sustainability*, *14*(3), p.1930.

[14] Cheraghi, Y., Kord, S. and Mashayekhizadeh, V., 2021. Application of machine learning techniques for selecting the most suitable enhanced oil recovery method; challenges and opportunities. *Journal of Petroleum Science and Engineering*, *205*, p.108761.

[15] Damman, S., Sandberg, E., Rosenberg, E., Pisciella, P. and Johansen, U., 2020. Largescale hydrogen production in Norway-possible transition pathways towards 2050. *SINTEF Rapport*.

[16] Dawood, F., Anda, M. and Shafiullah, G.M., 2020. Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*, *45*(7), pp.3847-3869.

[17] De Blasio, N., Krishnamoorthy, S., Kapadia, Z., Mayer, A., Schiele, J. and Sweeney-Taylor, A., 2020. Deploying Energy Innovation at Scale for a Low-Carbon Economy: The Private Sector Role-ENGIE. *Environment and Natural Resources Program Papers*.

[18] Dincer, I. and Aydin, M.I., 2023. New paradigms in sustainable energy systems with hydrogen. *Energy Conversion and Management*, *283*, p.116950.

[19] Furfari, S. and Clerici, A., 2021. Green hydrogen: the crucial performance of electrolysers fed by variable and intermittent renewable electricity. *The European Physical Journal Plus*, *136*(5), p.509.

[20] Gordon, J.A., Balta-Ozkan, N. and Nabavi, S.A., 2023. Socio-technical barriers to domestic hydrogen futures: repurposing pipelines, policies, and public perceptions. *Applied Energy*, *336*, p.120850.

[21] Green, J., Hadden, J., Hale, T. and Mahdavi, P., 2022. Transition, hedge, or resist? Understanding political and economic behavior toward decarbonization in the oil and gas industry. *Review of international political economy*, *29*(6), pp.2036-2063.

[22] Guilbert, D. and Vitale, G., 2021. Hydrogen as a clean and sustainable energy vector for global transition from fossil-based to zero-carbon. *Clean Technologies*, *3*(4), pp.881-909.

[23] Guo, Y., Yang, Y., Bradshaw, M., Wang, C. and Blondeel, M., 2023. Globalization and decarbonization: Changing strategies of global oil and gas companies. *Wiley Interdisciplinary Reviews: Climate Change*, *14*(6), p.e849.

[24] Harichandan, S. and Kar, S.K., 2023. Financing the hydrogen industry: exploring demand and supply chain dynamics. *Environmental Science and Pollution Research*, pp.1-18.

[25] Hassan, Q., Sameen, A.Z., Salman, H.M., Jaszczur, M. and Al-Jiboory, A.K., 2023. Hydrogen energy future: Advancements in storage technologies and implications for sustainability. *Journal of Energy Storage*, *72*, p.108404.

[26] Hill, L.B., Li, X. and Wei, N., 2020. CO2-EOR in China: A comparative review. *International Journal of Greenhouse Gas Control*, *103*, p.103173.

[27] Hosseini, S.E. and Butler, B., 2020. An overview of development and challenges in hydrogen powered vehicles. *International journal of green energy*, *17*(1), pp.13-37.

[28] Ishaq, H., Dincer, I. and Crawford, C., 2022. A review on hydrogen production and utilization: Challenges and opportunities. *International Journal of Hydrogen Energy*, *47*(62), pp.26238-26264.

[29] Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J. and Jäger-Waldau, A., 2021. Green hydrogen in Europe–A regional assessment: Substituting existing production with electrolysis powered by renewables. *Energy conversion and management*, *228*, p.113649.

[30] Kang, W.L., Zhou, B.B., Issakhov, M. and Gabdullin, M., 2022. Advances in enhanced oil recovery technologies for low permeability reservoirs. *Petroleum Science*, *19*(4), pp.1622-1640.

[31] Karpyn, A., McCallops, K., Wolgast, H. and Hepburn, E., 2021. Public-private partnerships to promote healthy food access. In *Partnerships for the Goals* (pp. 989-1000). Cham: Springer International Publishing.

[32] Khan, M.H.A., Daiyan, R., Neal, P., Haque, N., MacGill, I. and Amal, R., 2021. A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation. *International Journal of Hydrogen Energy*, *46*(44), pp.22685-22706.

[33] Kovač, A., Paranos, M. and Marciuš, D., 2021. Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy*, *46*(16), pp.10016-10035.

[34] Lau, H.C., Ramakrishna, S., Zhang, K. and Radhamani, A.V., 2021. The role of carbon capture and storage in the energy transition. *Energy & Fuels*, *35*(9), pp.7364-7386.

[35] Li, X., Raorane, C.J., Xia, C., Wu, Y., Tran, T.K.N. and Khademi, T., 2023. Latest approaches on green hydrogen as a potential source of renewable energy towards sustainable energy: Spotlighting of recent innovations, challenges, and future insights. *Fuel*, *334*, p.126684.

[36] Litvinenko, V.S., Tsvetkov, P.S., Dvoynikov, M.V. and Buslaev, G.V., 2020. Barriers to implementation of hydrogen initiatives in the context of global energy sustainable development. *Записки Горного Института*, *244*, pp.428-438.

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

[38] Moretto, P. and Quong, S., 2022. Legal requirements, technical regulations, codes, and standards for hydrogen safety. In *Hydrogen safety for energy applications* (pp. 345-396). Butterworth-Heinemann.

[39] Nazir, H., Muthuswamy, N., Louis, C., Jose, S., Prakash, J., Buan, M.E., Flox, C., Chavan, S., Shi, X., Kauranen, P. and Kallio, T., 2020. Is the H2 economy realizable in the foreseeable future? Part III: H2 usage technologies, applications, and challenges and opportunities. *International journal of hydrogen energy*, *45*(53), pp.28217-28239.

[40] Nong, D., Simshauser, P. and Nguyen, D.B., 2021. Greenhouse gas emissions vs CO2 emissions: Comparative analysis of a global carbon tax. *Applied Energy*, *298*, p.117223.

[41] Noussan, M., Raimondi, P.P., Scita, R. and Hafner, M., 2020. The role of green and blue hydrogen in the energy transition—A technological and geopolitical perspective. *Sustainability*, *13*(1), p.298.

[42] Ohaeri, E., Eduok, U. and Szpunar, J., 2018. Hydrogen related degradation in pipeline steel: A review. *International Journal of Hydrogen Energy*, *43*(31), pp.14584-14617.

[43] Patlolla, S.R., Katsu, K., Sharafian, A., Wei, K., Herrera, O.E. and Mérida, W., 2023. A review of methane pyrolysis technologies for hydrogen production. *Renewable and Sustainable Energy Reviews*, *181*, p.113323.

[44] Pingkuo, L. and Xue, H., 2022. Comparative analysis on similarities and differences of hydrogen energy development in the World's top 4 largest economies: a novel framework. *International Journal of Hydrogen Energy*, *47*(16), pp.9485-9503.

[45] Rasaki, S.A., Liu, C., Lao, C., Zhang, H. and Chen, Z., 2021. The innovative contribution of additive manufacturing towards revolutionizing fuel cell fabrication for clean energy generation: A comprehensive review. *Renewable and sustainable energy reviews*, *148*, p.111369.

[46] Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow III, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B. and Cresko, J., 2020. Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied energy*, *266*, p.114848.

[47] Rolo, I., Costa, V.A. and Brito, F.P., 2023. Hydrogen-Based Energy Systems: Current Technology Development Status, Opportunities and Challenges. *Energies*, *17*(1), p.180.

[48] Saha, D., Shrestha, R. and Feldmann, J., 2021. Designing the Next Generation of Federal Tax Credits for Low-Carbon Technologies. *World Resources Institute. Working Paper. June*.

[49] Sazali, N., 2020. Emerging technologies by hydrogen: A review. *International Journal of Hydrogen Energy*, *45*(38), pp.18753-18771.

[50] Sebbahi, S., Nabil, N., Alaoui-Belghiti, A., Laasri, S., Rachidi, S. and Hajjaji, A., 2022. Assessment of the three most developed water electrolysis technologies: alkaline water electrolysis, proton exchange membrane and solid-oxide electrolysis. *Materials Today: Proceedings*, *66*, pp.140-145.

[51] Sekar, L.K., Kiran, R., Okoroafor, E.R. and Wood, D.A., 2023. Review of reservoir challenges associated with subsurface hydrogen storage and recovery in depleted oil and gas reservoirs. *Journal of Energy Storage*, *72*, p.108605.

[52] Tashie-Lewis, B.C. and Nnabuife, S.G., 2021. Hydrogen production, distribution, storage and power conversion in a hydrogen economy-a technology review. *Chemical Engineering Journal Advances*, *8*, p.100172.

[53] Telegina, E.A. and Chapaikin, D.A., 2022. Directions of the energy transition in the policy of global oil and gas companies. *Studies on Russian Economic Development*, *33*(5), pp.555-560.

[54] Tsiklios, C., Hermesmann, M. and Müller, T.E., 2022. Hydrogen transport in large-scale transmission pipeline networks: Thermodynamic and environmental assessment of repurposed and new pipeline configurations. *Applied Energy*, *327*, p.120097.

[55] Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W. and Lenaerts, S., 2021. Challenges in the use of hydrogen for maritime applications. *Energy & Environmental Science*, *14*(2), pp.815-843.

[56] Yang, M., Hunger, R., Berrettoni, S., Sprecher, B. and Wang, B., 2023. A review of hydrogen storage and transport technologies. *Clean Energy*, *7*(1), pp.190-216.

[57] Yu, S., Fan, Y., Shi, Z., Li, J., Zhao, X., Zhang, T. and Chang, Z., 2023. Hydrogen-based combined heat and power systems: A review of technologies and challenges. *International Journal of Hydrogen Energy*, *48*(89), pp.34906-34929.

[58] Zakaria, Z., Kamarudin, S.K., Salehmin, M.N.I., Ahmad, N.N.R., Aminuddin, M.A., Hanapi, I.H., Osman, S.H. and Mohamad, A.A., 2023. Energy scenario in Malaysia: Embarking on the potential use of hydrogen energy. *International Journal of Hydrogen Energy*, *48*(91), pp.35685-35707.

[59] Zhang, B., Zhang, S.X., Yao, R., Wu, Y.H. and Qiu, J.S., 2021. Progress and prospects of hydrogen production: Opportunities and challenges. *Journal of Electronic Science and Technology*, *19*(2), p.100080.

[60] Zou, C., Li, J., Zhang, X., Jin, X., Xiong, B., Yu, H., Liu, X., Wang, S., Li, Y., Zhang, L. and Miao, S., 2022. Industrial status, technological progress, challenges, and prospects of hydrogen energy. *Natural Gas Industry B*, *9*(5), pp.427-447.