Carbon Capture, Utilization, and Storage (CCUS) in Offshore and Onshore Oil Platforms

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ABSTRACT

Carbon Capture, Utilization, and Storage (CCUS) is a critical technology for reducing CO2 emissions in the oil and gas sector, contributing to global decarbonization efforts. This review explores the integration of CCUS technology in both offshore and onshore oil platforms, focusing on capturing CO2 emissions and either utilizing it for enhanced oil recovery (EOR) or storing it underground. The review begins with an overview of CCUS mechanisms, including CO2 capture techniques, utilization in industrial applications such as EOR, and storage in geological formations. The analysis delves into the unique challenges and opportunities associated with CCUS deployment in offshore platforms, including infrastructure requirements, marine environment considerations, and case studies of successful offshore projects like Norway's Sleipner. Onshore oil platforms are also examined, with a focus on proximity to CO2 sources, infrastructure costs, and notable onshore CCUS initiatives. The review highlights the dual benefits of CO2-EOR, which boosts oil recovery while simultaneously sequestering CO2, extending the operational life of oil fields. However, challenges such as the technical barriers to CO2 retention, high costs, and regulatory uncertainties are discussed. Technological innovations, including advanced capture methods and improved storage monitoring, are identified as potential pathways to overcoming these obstacles. Future prospects for large-scale CCUS deployment are considered, emphasizing the need for public-private partnerships, policy support, and investment to scale up the technology and ensure its role in achieving net-zero emissions. This review underscores the importance of CCUS in reducing the environmental impact of oil and gas operations, while offering economic incentives through EOR and the long-term potential for sustainable energy transition.

Keywords: Carbon Capture, CCUS Oil, Platforms, Review

INTRODUCTION

Carbon Capture, Utilization, and Storage (CCUS) is a suite of technologies designed to address the increasing concern over carbon dioxide (CO2) emissions, particularly in industries with significant greenhouse gas outputs, such as oil and gas (Jiang and Ashworth, 2021; Bajpai *et al*., 2022). Carbon Capture involves capturing CO2 emissions at their source such as power plants, industrial facilities, and oil and gas operations before they can enter the atmosphere. Utilization refers to the various methods by which captured CO2 can be repurposed, typically for use in industrial processes or as a feedstock for creating valuable products (Koytsoumpa *et al*., 2018). Finally, Storage involves safely sequestering CO2 in geological formations underground to prevent its release into the atmosphere.

The oil and gas industry, a major contributor to global CO2 emissions, plays a pivotal role in the advancement and implementation of CCUS technologies (Deng *et al*., 2022). With fossil fuels projected to remain a significant energy source in the near future, the integration of CCUS within oil and gas operations is essential for achieving sustainability objectives and mitigating climate change. According to the International Energy Agency (IEA), CCUS could account for approximately 15% of the total reductions needed to limit global temperature rise to below 2°C, as outlined in the Paris Agreement (Page *et al*., 2020; Regufe *et al*., 2021). This highlights the importance of CCUS not just as a complementary technology, but as a crucial component of a comprehensive strategy for decarbonization in the energy sector.

Furthermore, CCUS technologies are increasingly relevant to global decarbonization efforts and climate change goals. As nations strive to meet their commitments under international climate agreements, the need for effective carbon management solutions becomes ever more pressing (Kinley *et al*., 2021). By implementing CCUS, countries can bridge the gap between current fossil fuel dependence and a future characterized by lower carbon emissions. This makes CCUS a critical focus area for policymakers, researchers, and industry leaders alike, as it represents a viable pathway to both economic growth and environmental stewardship (Chen *et al*., 2022).

The purpose of this review is to explore the integration of CCUS technology into both offshore and onshore oil platforms, assessing the potential benefits and challenges associated with its implementation. Offshore platforms, often situated in remote locations, face unique logistical and operational challenges when adopting CCUS technologies. Conversely, onshore facilities may have more accessible infrastructure but encounter different regulatory and technical hurdles. By examining these two contexts, we can better understand how CCUS can be effectively tailored to meet the specific needs and conditions of various oil and gas operations. Moreover, this review will provide an overview of how captured CO2 can be utilized for Enhanced Oil Recovery (EOR) or stored underground in geological formations. EOR is a crucial method that not only improves oil recovery rates but also serves as a mechanism for utilizing captured CO2, thereby reducing the overall carbon footprint of oil extraction processes. This dual approach capturing and utilizing CO2 illustrates the potential for synergy between carbon management and resource recovery, offering a practical and economically viable pathway for the oil and gas industry. This aims to present a comprehensive analysis of CCUS technologies and their integration into oil and gas operations. By highlighting the definition, importance, and relevance of CCUS in mitigating CO2 emissions, we set the stage for a deeper examination of its applications in both offshore and onshore contexts. Furthermore, by exploring the dual role of captured CO2 in EOR and underground storage, we emphasize the multifaceted benefits that CCUS technologies can bring to the oil and gas industry as it navigates the complexities of a transitioning energy landscape. Through this exploration, we hope to contribute to the ongoing dialogue surrounding sustainable practices in oil and gas and the essential role of innovative technologies in combating climate change.

CCUS Technology in the Oil and Gas Industry

The oil and gas industry faces increasing scrutiny regarding its role in climate change, particularly due to the significant carbon dioxide (CO2) emissions associated with fossil fuel extraction and consumption (Okeke, 2021; Kenner and Heede, 2021). To address this issue, Carbon Capture, Utilization, and Storage (CCUS) technology has emerged as a vital solution for reducing greenhouse gas emissions while allowing the continued use of fossil fuels. This review explores the mechanisms of CCUS technology, its integration into oil and gas operations, and the associated benefits.

CCUS technology encompasses several techniques for capturing CO2 emissions from industrial processes. The primary methods of carbon capture include. Post-Combustion Capture technique captures CO2 from the flue gases emitted after combustion. It utilizes chemical solvents, such as amines, to absorb CO2 from the gas stream (Asif *et al*., 2018). Post-combustion capture is advantageous for existing power plants and industrial facilities, as it can be retrofitted without significant changes to the infrastructure. Pre-Combustion Capture method, fossil fuels are converted into a gas mixture consisting of hydrogen and CO2 before combustion. The CO2 is then separated and captured, allowing the hydrogen to be used as a clean energy source. Pre-combustion capture is often used in integrated gasification combined cycle (IGCC) plants, where the carbon content is significantly reduced before it can enter the combustion process. Oxyfuel Combustion technique involves burning fossil fuels in an environment enriched with oxygen instead of air, resulting in a flue gas composed primarily of CO2 and water vapor. The water vapor can be easily condensed and removed, leaving behind a concentrated CO2 stream that is easier to capture and store (Anwar *et al*., 2018). Oxyfuel combustion is particularly beneficial for new power plants designed for CCUS integration.

Once CO2 is captured, it can be utilized in various ways, with Enhanced Oil Recovery (EOR) being one of the most prominent applications. EOR involves injecting CO2 into depleted oil reservoirs to increase pressure and improve oil recovery rates (Hamza e al., 2021). This method not only helps extend the life of mature oil fields but also provides a practical application for the captured CO2, effectively reducing the overall carbon footprint

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of oil extraction operations. In addition to EOR, captured CO2 can be utilized in other industrial applications, such as the production of chemicals, fuels, and building materials. For instance, CO2 can be converted into methanol or urea, both of which have significant market demand. This broadens the scope of carbon utilization beyond just the oil and gas sector, presenting opportunities for innovative applications across multiple industries.

The final component of CCUS involves the long-term storage of captured CO2 in geological formations. This process typically involves injecting CO2 into suitable underground reservoirs, such as. Deep Saline Aquifers formations contain highly saline water and have significant storage capacity. They are widespread and can store large volumes of CO2, making them a preferred option for long-term storage. Depleted Oil Fields, having already been exploited for oil extraction, provide an established infrastructure for CO2 injection and can securely store CO2 while simultaneously supporting EOR efforts (Hill *et al*., 2020). Utilizing these sites can minimize the need for new infrastructure development and enhance overall economic feasibility. By effectively capturing, utilizing, and storing CO2, CCUS technology enables the oil and gas industry to mitigate its carbon emissions significantly.

By implementing CCUS, oil and gas facilities can substantially reduce their carbon footprint. This is particularly important in light of global climate targets aimed at limiting temperature rise. By capturing CO2 emissions at their source, these facilities can minimize the amount of greenhouse gases released into the atmosphere, aligning with sustainability goals and regulatory requirements. The application of EOR not only enhances oil recovery rates but also prolongs the operational lifespan of mature oil fields. As conventional oil reserves become depleted, EOR techniques using captured CO2 offer a viable solution for maximizing resource extraction (Núñez-López and Moskal, 2019). This not only has economic implications for operators but also supports energy security by optimizing existing resources. The economic incentives for adopting CCUS technologies are significant. Facilities that implement these systems can benefit from government incentives, carbon credits, and potential cost savings associated with increased oil production through EOR. Additionally, companies adopting CCUS technologies may enhance their public image as responsible corporate citizens committed to reducing environmental impacts. CCUS technology represents a critical avenue for the oil and gas industry to reduce its carbon emissions while continuing to operate in a carbon-constrained environment. By effectively capturing CO2, utilizing it for EOR and other applications, and securely storing it underground, the oil and gas sector can align itself with global decarbonization efforts and contribute positively to climate change mitigation goals. The integration of CCUS not only provides a pathway to sustainability but also offers economic advantages, making it a vital component of the industry's transition toward a low-carbon future (Mikulčić *et al*., 2019).

CCUS Integration in Offshore Oil Platforms

As the global demand for energy continues to rise amidst increasing concerns over climate change, the oil and gas industry faces significant pressure to reduce carbon dioxide (CO2) emissions (Ope *et al*., 2022). Carbon Capture, Utilization, and Storage (CCUS) technology has emerged as a critical solution to mitigate these emissions, particularly in offshore oil platforms where conventional approaches may not suffice. This review examines the technical and operational challenges associated with integrating CCUS in offshore environments, the potential advantages of such integration, and notable case studies that demonstrate successful implementations of offshore CCUS projects.

Integrating CCUS technology in offshore oil platforms necessitates substantial infrastructure development, including pipelines for transporting captured CO2, storage sites for long-term sequestration, and modifications to existing offshore facilities. The offshore environment poses unique challenges, such as the need for robust and corrosion-resistant materials capable of withstanding harsh marine conditions (Olajire, 2018). Moreover, the installation and maintenance of pipelines for CO2 transport require careful planning to ensure safety and reliability, as these pipelines must often traverse challenging underwater terrains. Offshore platforms operate in environments characterized by high winds, waves, and saltwater exposure, which can adversely impact CCUS operations. The equipment used for capturing, compressing, and transporting CO2 must be designed to withstand these extreme conditions, which can increase capital costs and complicate maintenance procedures. Additionally, potential impacts on marine ecosystems must be carefully considered during the planning and implementation phases to avoid environmental degradation. The transportation of captured CO2 from offshore platforms to storage or utilization sites presents another layer of complexity. Efficient logistics are crucial for minimizing costs and maximizing the effectiveness of CCUS operations (Zhang *et al*., 2020). Options for CO2 transportation include pipelines, ships, and barges, each with distinct advantages and limitations. The choice of transportation method must consider factors such as distance, volume, and operational efficiency. Moreover, the design of these transportation systems must ensure that the captured CO2 remains in a supercritical state, which is necessary for efficient transport and storage.

One of the most significant advantages of integrating CCUS into offshore oil platforms is the availability of depleted oil and gas reservoirs for CO2 storage. These reservoirs, which have already demonstrated their capacity to contain hydrocarbons, provide a secure and reliable option for long-term CO2 sequestration. Utilizing these existing geological formations can reduce the need for extensive geological surveys and new site developments, making the integration of CCUS more economically viable (Sowiżdżał *et al*., 2022). The integration of CCUS technology can create synergies between offshore oil operations and carbon sequestration efforts. By capturing CO2 from the combustion processes associated with oil extraction and transportation, offshore platforms can significantly reduce their overall emissions. Additionally, the revenue generated from enhanced oil recovery (EOR) methods that utilize captured CO2 can provide a financial incentive for implementing CCUS technologies. This synergy not only helps to mitigate the carbon footprint of oil production but also fosters a more sustainable business model for offshore operators (Basile *et al*., 2021).

Several successful offshore CCUS projects illustrate the feasibility and effectiveness of integrating CCUS technology into oil operations. One of the most notable examples is Norway's Sleipner project, which has been operational since 1996. Located in the North Sea, the Sleipner project captures approximately one million tons of CO2 annually from natural gas production and stores it in a deep saline aquifer beneath the seabed. This project not only demonstrates the technical viability of offshore CO2 storage but also serves as a model for other countries looking to implement similar initiatives. Another example is the Gorgon Project in Australia, which incorporates CCUS as a central component of its liquefied natural gas (LNG) production (Marshall, 2022). Gorgon captures and stores approximately 4 million tons of CO2 annually, injecting it into a deep geological formation beneath Barrow Island. The project has successfully navigated the technical and regulatory challenges associated with offshore CO2 storage and has become a key player in Australia's efforts to reduce emissions from fossil fuel operations. Furthermore, the UK's Acorn Project aims to utilize existing oil and gas infrastructure for capturing and storing CO2 from various industrial sources. By repurposing decommissioned offshore facilities, the Acorn Project highlights the potential for integrating CCUS into a broader strategy for decarbonizing the energy sector. Integrating CCUS technology into offshore oil platforms presents both challenges and opportunities for the oil and gas industry in its quest to reduce carbon emissions. While technical and operational hurdles such as infrastructure requirements, harsh marine environments, and transportation logistics must be addressed, the potential advantages including the availability of depleted reservoirs for storage and synergies between oil operations and carbon sequestration offer promising pathways for sustainable development. Successful case studies like Norway's Sleipner project and Australia's Gorgon Project provide valuable insights into the practical implementation of CCUS in offshore settings. As the industry continues to evolve, CCUS will play a crucial role in achieving climate goals while ensuring the continued viability of offshore oil and gas operations (Vishal *et al*., 2021).

CCUS Integration in Onshore Oil Platforms

As the urgency to combat climate change intensifies, the integration of Carbon Capture, Utilization, and Storage (CCUS) technologies within onshore oil platforms emerges as a pivotal strategy for reducing greenhouse gas emissions (Jiang *et al*., 2020). This explores the key considerations for implementing CCUS in onshore settings, discusses the advantages and limitations of such integration, and examines notable case studies that exemplify successful onshore CCUS initiatives.

One of the foremost considerations for integrating CCUS in onshore oil platforms is the proximity to CO2 emission sources and suitable geological storage sites. Effective carbon capture requires the availability of significant CO2 emissions, typically generated by industrial processes, power generation, or oil extraction activities. The geographical location of these sources in relation to onshore oil platforms can significantly impact the feasibility of CCUS projects (Eide *et al.*, 2019). Furthermore, the selection of geological formations for CO2 storage is crucial. Ideal storage sites, such as deep saline aquifers or depleted oil and gas reservoirs, should be located nearby to minimize transportation logistics and costs. Accessibility to these sites will influence the design and implementation of transportation infrastructure, which must ensure safe and efficient CO2 injection and monitoring. Effective coordination between emission sources and storage locations is essential for optimizing the overall efficiency of CCUS systems. Integrating CCUS technologies requires substantial onshore infrastructure to facilitate the transportation and injection of captured CO2. This includes the construction of pipelines to transport CO2 from capture sites to geological storage locations. The design and installation of these pipelines must consider factors such as terrain, environmental impacts, and regulatory requirements (Cianciarullo, 2019). The development of injection wells for CO2 sequestration also necessitates careful planning and engineering. These wells must be designed to withstand the pressures and temperatures associated with CO2 injection while ensuring the integrity of the geological formations. Additionally, monitoring systems must be implemented to track the behavior of injected CO2 and ensure its long-term containment, further necessitating investment in infrastructure.

One of the significant advantages of integrating CCUS into onshore oil platforms is the generally lower transportation costs associated with CO2 logistics. Onshore pipelines can be more easily constructed and maintained than their offshore counterparts, leading to reduced capital expenditures and operational costs (Kaiser and Liu, 2018). The flexibility of onshore systems allows for more efficient routing of pipelines, minimizing transportation distances between capture sites and storage locations. Moreover, the integration of CCUS within existing oil and gas infrastructure can further reduce costs. Many onshore oil platforms already possess the necessary facilities and expertise for managing CO2 emissions, making the transition to CCUS more economically viable compared to developing new offshore systems. Despite the advantages, the integration of CCUS into onshore oil platforms also presents challenges, particularly regarding land use and community concerns. The construction of pipelines and storage facilities may conflict with existing land uses, such as agriculture, residential areas, and protected natural spaces. This can lead to opposition from local communities and stakeholders, necessitating careful engagement and transparent communication strategies. Community concerns about potential environmental impacts, including the risks associated with CO2 injection and the long-term stability of storage sites, must also be addressed. Public acceptance is crucial for the successful implementation of CCUS projects, and fostering trust through effective community outreach and education initiatives is essential (Nielsen *et al.*, 2022).

Several notable onshore CCUS initiatives demonstrate the potential of integrating these technologies into oil platforms effectively. The Alberta Carbon Trunk Line in Canada is one of the largest integrated CCUS projects in the world. This system captures CO2 emissions from multiple industrial sources and transports them via a 240-kilometer pipeline to enhance oil recovery operations and for permanent storage in deep saline aquifers. The ACTL project exemplifies the synergy between carbon capture and oil production, significantly reducing greenhouse gas emissions while maximizing resource recovery (Biermann, 2022). The Permian Basin in Texas is another prime example of successful onshore CCUS integration. The region has a robust network of oil and gas infrastructure, enabling the effective implementation of CO2 injection for enhanced oil recovery. Various operators in the Permian Basin are leveraging captured CO2 from industrial processes to boost oil production while simultaneously reducing their carbon footprint. This initiative showcases how established oil fields can transition towards more sustainable practices through the incorporation of CCUS technologies.

The integration of CCUS technologies into onshore oil platforms represents a critical strategy for reducing CO2 emissions and promoting sustainable energy practices (Li, 2022). Key considerations such as proximity to CO2 sources and geological storage sites, along with the development of onshore infrastructure, play essential roles in the successful implementation of these technologies. While advantages such as lower transportation costs exist, challenges related to land use and community acceptance must be carefully managed. Case studies like the Alberta Carbon Trunk Line and initiatives in the Permian Basin provide valuable insights into the potential for CCUS integration in onshore settings. As the urgency for climate action increases, CCUS will be vital for enabling the oil and gas industry to meet its decarbonization goals while ensuring continued energy production (Al Baroudi *et al.*, 2021).

Enhanced Oil Recovery (EOR) and CO2 Utilization

Enhanced Oil Recovery (EOR) is a pivotal technology in maximizing oil extraction from reservoirs, extending the life of existing oil fields, and significantly increasing recovery rates. Among the various methods employed in EOR, carbon dioxide (CO2) utilization has gained prominence due to its dual benefits: improving oil recovery while contributing to carbon sequestration (Mishra *et al*., 2019; Godin *et al*., 2021). This review explores the role of CO2 in EOR, the challenges associated with its implementation, and successful examples of CO2-EOR projects worldwide.

The primary mechanism through which CO2 enhances oil recovery involves its unique properties as a solvent. When CO2 is injected into oil reservoirs, it dissolves in the oil, reducing its viscosity and interfacial tension, thereby making it easier to mobilize and extract. The CO2 injection also increases reservoir pressure, facilitating the flow of oil toward production wells (Burrows *et al*., 2020). This process, known as CO2 flooding, can recover an additional 5 to 20% of the original oil in place, depending on the reservoir characteristics. Furthermore, CO2-EOR offers a dual benefit: economic gain and carbon sequestration. As oil recovery rates improve, operators can achieve greater profits from existing fields, making CO2-EOR economically attractive. Simultaneously, the CO2 injected into the reservoir can remain trapped underground for long periods, mitigating greenhouse gas emissions. This sequestration potential plays a critical role in global efforts to combat climate change by reducing the overall carbon footprint of fossil fuel extraction.

Despite its benefits, CO2-EOR faces several challenges that can hinder its widespread adoption. One significant concern is the monitoring and verification of CO2 retention during and after EOR operations. Ensuring that the injected CO2 does not escape back to the atmosphere is crucial for the effectiveness of carbon sequestration. Advanced monitoring techniques, such as seismic imaging and pressure monitoring, are essential to detect potential leaks and assess the long-term stability of CO2 storage (Fibbi *et al*., 2022). Additionally, the economic feasibility of CO2-EOR varies across different regions, influenced by factors such as local oil prices, infrastructure availability, and regulatory frameworks. In some areas, the cost of capturing, transporting, and injecting CO2 can be prohibitively high, making CO2-EOR less attractive compared to other methods. Furthermore, market demand for CO2-EOR is closely tied to the price of oil; low oil prices can diminish the economic viability of CO2-EOR projects, leading to hesitance from investors.

Despite these challenges, several successful CO2-EOR projects demonstrate the potential for integrating CO2 utilization into oil recovery (Song *et al*., 2020). One notable example is the Weyburn-Midale project in Saskatchewan, Canada, which has been operational since the late 1990s. This project has injected over 30 million tons of CO2 into the reservoirs and successfully increased oil recovery while sequestering significant amounts of CO2. The Weyburn-Midale project showcases the synergy between EOR and carbon sequestration, serving as a model for similar initiatives worldwide. Another successful project is the Lost Hills Oil Field in California, which began utilizing CO2-EOR in the early 2000s. This field has demonstrated substantial increases in oil recovery rates, with CO2 injection contributing to the extraction of millions of barrels of oil. The project has also highlighted the importance of collaboration between oil companies, government agencies, and research institutions in addressing the technical and regulatory challenges associated with CO2-EOR. In Norway, the Sleipner project in the North Sea is a pioneering example of combining CO2 capture and storage (CCS) with EOR. Since its inception in 1996, the Sleipner project has injected approximately 1 million tons of CO2 annually into a saline aquifer, demonstrating effective long-term CO2 storage. While the primary focus of Sleipner is on carbon sequestration, the integration of EOR techniques could enhance oil recovery in the region, showcasing the versatility of CO2 utilization (Adu *et al*., 2019).

Enhanced Oil Recovery utilizing CO2 presents a promising avenue for maximizing oil extraction while simultaneously addressing climate change through carbon sequestration. The mechanisms of CO2-EOR enhance oil recovery rates, offering economic benefits that can sustain the oil industry. However, challenges related to monitoring CO2 retention and economic feasibility must be addressed to ensure the viability of these projects. Successful examples like Weyburn-Midale, Lost Hills, and Sleipner highlight the potential of CO2-EOR and its role in a sustainable energy future. As technology and regulatory frameworks evolve, CO2-EOR can play a crucial role in balancing energy needs with environmental responsibilities (Yang *et al*., 2019).

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Challenges and Barriers to CCUS Deployment

Carbon Capture, Utilization, and Storage (CCUS) is a critical technology in the effort to mitigate climate change by reducing greenhouse gas emissions from industrial processes and power generation. Despite its potential, the deployment of CCUS faces numerous challenges and barriers that hinder its widespread adoption (Greig and Uden, 2021). These challenges can be broadly categorized into technical barriers, economic and financial constraints, and regulatory and policy issues.

Technical barriers are among the most significant challenges to the deployment of CCUS. The efficiency of CO2 capture technologies is a primary concern. While various technologies exist for capturing CO2, such as post-combustion capture, pre-combustion capture, and direct air capture, each has its limitations in terms of energy consumption, cost, and capture efficiency. Current capture technologies can be energy-intensive, requiring significant amounts of heat or electricity to operate, which can negate some of the environmental benefits of capturing CO2 (Dubey and Arora, 2022). Furthermore, the variability in CO2 concentration in different industrial processes complicates the design of efficient capture systems, necessitating tailored solutions that may not be economically feasible at scale. Safe and long-term storage of CO2 presents another technical challenge. While geological formations such as depleted oil and gas fields and deep saline aquifers have been identified as potential storage sites, ensuring the integrity and security of these storage sites over time is critical. The risk of leakage from storage sites could undermine public confidence in CCUS technology and negate the benefits of CO2 capture. Developing reliable monitoring systems to track CO2 storage and assess potential leakage is essential, but these systems require advanced technology and significant investment (Mortezaei *et al*., 2018).

Economic and financial constraints significantly impact the viability of CCUS deployment. One of the main challenges is the high upfront costs associated with CCUS infrastructure development (Rakhiemah and Xu, 2022). The capital required for building CO2 capture facilities, transportation pipelines, and storage sites can be prohibitively high, deterring investment. Additionally, the operational costs associated with running and maintaining CCUS systems can be substantial, especially if the efficiency of capture technologies does not improve significantly. This high cost is particularly concerning for industries with thin profit margins, where the additional expenses of CCUS could render them uncompetitive. Market uncertainty around carbon pricing and financial incentives further complicates the economic landscape for CCUS. The effectiveness of CCUS often hinges on the existence of a robust carbon pricing mechanism or financial incentives to support the technology's deployment. However, the variability in carbon pricing and the lack of clear and consistent government policies create uncertainty for potential investors. Without guaranteed financial returns, companies may be reluctant to commit to CCUS projects, stalling the development of necessary infrastructure and technologies (Makuch *et al*., 2020).

Regulatory and policy issues also play a critical role in shaping the landscape for CCUS deployment (Reyes-Lúa and Jordal, 2020). Government regulations and international climate agreements significantly influence the adoption of CCUS technologies. While many governments recognize the importance of CCUS in achieving climate goals, regulatory frameworks often lag behind technological advancements. Inconsistent regulations across regions can create challenges for companies operating in multiple jurisdictions, complicating investment decisions and slowing down deployment efforts (Teece, 2020). Additionally, international climate agreements can impact the willingness of countries to invest in CCUS technologies, particularly if there is a lack of consensus on global emissions reduction targets. Legal frameworks for CO2 storage present another regulatory challenge (Gola and Noussia, 2022). Questions around liability and ownership of stored CO2 can deter investment in CCUS projects. If CO2 leaks from a storage site, determining responsibility for environmental damage can be complicated. Clear legal frameworks that outline liability and responsibility are necessary to provide confidence to investors and operators in the CCUS space. Establishing regulatory clarity on these issues will be crucial to overcoming the barriers to CCUS deployment (Zhang, 2021).

While Carbon Capture, Utilization, and Storage (CCUS) offers significant potential for reducing greenhouse gas emissions, its deployment is hindered by various challenges and barriers. Technical limitations, including the efficiency of CO2 capture technologies and the safe storage of CO2, pose significant hurdles. Economic and financial constraints, characterized by high upfront costs and market uncertainty, further complicate the landscape for CCUS (Sareen and Sagmo, 2021). Finally, regulatory and policy issues, including inconsistent government regulations and legal uncertainties surrounding CO2 storage, must be addressed to facilitate the widespread adoption of CCUS. Overcoming these challenges will require coordinated efforts among governments, industry stakeholders, and researchers to develop effective solutions and ensure the successful deployment of CCUS technologies in the fight against climate change (Shirmohammadi *et al*., 2020).

Future Prospects and Innovations in Carbon Capture, Utilization, and Storage (CCUS)

As the world grapples with the pressing need to mitigate climate change, Carbon Capture, Utilization, and Storage (CCUS) emerges as a vital technology for reducing greenhouse gas emissions (Sandunika *et al*., 2020). Looking ahead, several promising innovations and prospects in CCUS can significantly enhance its effectiveness and facilitate broader adoption across various sectors.

Technological innovations play a crucial role in advancing CCUS capabilities. Among these, advanced carbon capture methods, such as direct air capture (DAC), have garnered significant attention. DAC technologies utilize chemical processes to extract CO2 directly from the atmosphere, offering a unique solution to reducing atmospheric carbon levels (Mostafa *et al*., 2022). These systems, although still in their infancy, have the potential to scale up significantly, enabling large quantities of CO2 to be captured from ambient air. By improving the efficiency and cost-effectiveness of DAC technologies, we can create a viable method for offsetting emissions from sectors that are difficult to decarbonize. In parallel, improvements in CO2 storage monitoring and verification technologies are critical for ensuring the long-term security of captured carbon. Innovative approaches such as enhanced seismic imaging, remote sensing, and geochemical monitoring are being developed to assess the integrity of CO2 storage sites (Mortezaei *et al*., 2018). These advancements will provide operators with real-time data on CO2 behavior within geological formations, ensuring that it remains safely sequestered. Improved monitoring capabilities will enhance public confidence in CCUS, addressing concerns about potential leakage and enabling regulatory compliance.

The potential for large-scale deployment of CCUS is promising, especially as the technology expands beyond traditional oil and gas applications. Industries such as cement, steel, and chemical manufacturing, which are among the highest emitters of CO2, are increasingly recognizing the value of CCUS (Benhelal *et al*., 2021). By incorporating carbon capture technologies into their operations, these industries can significantly reduce their emissions while maintaining production efficiency. Furthermore, the expansion of CCUS into new regions offers the opportunity to harness local geological formations for CO2 storage, creating a more diverse and robust infrastructure (Zitelman *et al*., 2018). The role of CCUS in achieving net-zero emissions targets cannot be overstated. Many countries are setting ambitious climate goals, and CCUS is essential for meeting these commitments, particularly for hard-to-abate sectors (Ferrier *et al*., 2022). For instance, the International Energy Agency (IEA) has indicated that achieving net-zero emissions by 2050 will require a tenfold increase in CCUS capacity. By deploying CCUS at scale, we can effectively capture and utilize significant volumes of CO2, making substantial progress toward climate goals.

Realizing the full potential of CCUS will require extensive collaboration and investment from various stakeholders. Public-private partnerships (PPPs) are essential for driving CCUS development, combining the resources and expertise of both sectors (Goldthorpe and Avignon, 2021). By fostering collaboration between governments, industry players, and research institutions, we can accelerate technological advancements and streamline project deployment. Such partnerships can facilitate knowledge sharing, risk mitigation, and the pooling of financial resources necessary for large-scale CCUS initiatives. The role of governments and international bodies is also crucial in scaling up CCUS. Clear and consistent policies, including carbon pricing mechanisms and financial incentives, are needed to support investment in CCUS projects (Lin and Tan, 2021). International collaboration can further enhance CCUS development, allowing countries to share best practices, technology, and funding opportunities. Global agreements aimed at climate action must include provisions for CCUS, ensuring that it is integrated into broader sustainability strategies.

The future of Carbon Capture, Utilization, and Storage (CCUS) holds great promise, driven by technological innovations, the potential for large-scale deployment, and collaborative efforts among stakeholders (Sullivan *et al*., 2020; Lau *et al*., 2021). Advances in carbon capture methods and monitoring technologies will enhance the

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efficiency and reliability of CCUS. As the technology expands to new regions and industries, its critical role in achieving net-zero emissions targets will become increasingly apparent. To realize the full potential of CCUS, public-private partnerships and supportive government policies will be essential in fostering investment and collaboration (Mete *et al*., 2021). With these concerted efforts, CCUS can play a transformative role in the global transition to a sustainable and low-carbon future.

CONCLUSION

The integration of Carbon Capture, Utilization, and Storage (CCUS) technology in oil platforms presents a transformative opportunity for both offshore and onshore oil operations. One of the key benefits of incorporating CCUS in these settings is the enhancement of operational efficiency through Carbon Dioxide Enhanced Oil Recovery (CO2-EOR). By injecting captured CO2 into mature oil reservoirs, operators can not only extract additional oil but also significantly reduce greenhouse gas emissions associated with production activities. Furthermore, the storage of CO2 in geological formations offers a long-term solution for sequestering carbon, thereby mitigating the industry's overall carbon footprint.

As the global energy transition gains momentum, the outlook for CCUS in the oil and gas sector is increasingly promising. CCUS technologies have the potential to play a vital role in achieving climate goals by reducing emissions from one of the most carbon-intensive industries. By effectively capturing and utilizing CO2, the oil and gas sector can contribute to a more sustainable energy landscape, facilitating a gradual shift toward cleaner energy sources while maintaining energy security.

However, to realize the full potential of CCUS, continued research and innovation are essential. Investment in advanced capture technologies, improved monitoring systems, and supportive regulatory frameworks will be crucial for enhancing CCUS deployment. Additionally, policy support from governments and international bodies will help create a favorable environment for investment and collaboration in CCUS projects. With sustained efforts in research, funding, and policy development, CCUS can become a cornerstone of the oil and gas sector's transition toward a low-carbon future, supporting global efforts to combat climate change while ensuring energy needs are met.

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