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The integration of Artificial Intelligence in carbon capture, utilization and storage for environmental sustainability in the oil and gas industry

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Abstract

The oil and gas industry are the main driver of the world's greenhouse gas emissions and countermeasures are required to achieve international targets for reducing emissions. Carbon Capture, Utilization, and Storage technologies have become leading emission-reducing means but are constrained by high cost of operations, system complexity, and long-duration reliability. This review paper discusses the application of Artificial Iintelligence to Carbon Capture, Utilization, and Storage systems as one of the main pathways to enhancing environmental sustainability for the oil and gas industry. The review discusses recent advances in Artificial Intelligence, including deep learning, reinforcement learning, and machine learning, including means by which they are being applied to CCUS value chain, including CO_2 capture, transportation, storage, and utilization. This paper examines the roles played by AI to maximize capture process, pipeline leak prevention, capture process monitoring accuracy, and CO_2 utilization by enhanced oil recovery (EOR). It considers constraints and bottlenecks to AI applications including lack of data, models lack of interpretability, cybersecurity vulnerabilities, and limitations to interdisciplinary cooperation. The review concludes by asserting that despite limitations, AI holds revolutionary potential to make CCUS efficient, cost-sensitive, and scalable to position it as key enabler of industry transition to the era of low-carbon production.

Keywords: Artificial Intelligence (AI); Carbon Capture Utilization and Storage (CCUS); Oil and Gas Industry; Environmental Sustainability; Machine Learning Optimization

1. Introduction

The oil and gas industry are one of the largest contributors to global greenhouse gas (GHG) emissions, primarily through the release of carbon dioxide (CO_2) during fossil fuel extraction, processing, and combustion. With increasing environmental concerns and international agreements such as the Paris Agreement, the need to significantly reduce CO_2 emissions has become imperative [1]. Carbon Capture, Utilization, and Storage (CCUS) has emerged as a key technology for mitigating these emissions by capturing CO_2 from industrial sources and either storing it underground or reusing it in applications such as enhanced oil recovery (EOR) [2]. Despite its potential, CCUS faces major operational and economic challenges. These include the high energy demands of CO_2 capture, the risks of leakage during transportation and storage, and the complexities involved in monitoring and verifying CO_2 containment over long

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periods. As the oil and gas sector aims to align with global sustainability goals, innovative approaches are required to overcome these hurdles and make CCUS more efficient, scalable, and reliable [3].

1.1. Emergence of Artificial Intelligence in the Energy Sector

Artificial Intelligence (AI) has rapidly gained attention across industrial sectors for its ability to process vast datasets, recognize patterns, make predictions, and automate decision-making processes. In the energy sector, especially in oil and gas, AI has already been applied successfully to tasks such as predictive maintenance, seismic interpretation, drilling optimization, and production forecasting [4]. These successes have opened new avenues for the application of AI in environmental sustainability efforts, including CCUS. AI's strength lies in its capacity to improve accuracy, efficiency, and real-time responsiveness of systems that rely on large-scale data collection and complex models. In the context of CCUS, AI can be leveraged to enhance CO_2 capture efficiency, predict and prevent storage site leaks, optimize CO_2 transport logistics, and improve monitoring and reporting mechanisms. These capabilities not only lower costs and operational risks but also increase the credibility and scalability of CCUS as a long-term climate mitigation strategy [5].

1.2. Aim and Scope of the Review

This review aims to explore the current and emerging roles of AI in improving the effectiveness and sustainability of CCUS systems in the oil and gas industry. Specifically, it investigates how AI technologies ranging from machine learning algorithms to neural networks are being integrated into each stage of the CCUS value chain: from capture and compression to transportation, storage, and utilization. The scope of the paper includes a detailed examination of recent literature (2020–2025), practical case studies where AI has enhanced CCUS operations, and discussions on technological and regulatory challenges that may hinder AI deployment. Ultimately, this paper seeks to provide a comprehensive understanding of how AI can drive environmental innovation in one of the most emission-intensive sectors, and how its integration can support the global transition toward a low-carbon energy future.

2. Literature Review

2.1. Overview of CCUS in Oil & Gas

Carbon Capture, Utilization, and Storage (CCUS) is a suite of technologies designed to reduce carbon dioxide (CO_2) emissions from industrial sources by capturing CO_2, transporting it to storage or utilization sites, and either storing it in geological formations or repurposing it for industrial use [6]. In the oil and gas sector, CCUS plays a pivotal role not only in emissions reduction but also in supporting enhanced oil recovery (EOR), where captured CO_2 is injected into reservoirs to improve hydrocarbon recovery [7]. The three main components of CCUS include: Capture - Technologies include post-combustion (e.g., amine scrubbing), pre-combustion (e.g., gasification), and oxy-fuel combustion. These vary in terms of energy demand and cost. Transport - Mostly via pipelines, though ships and trucks are used for small-scale operations. Storage/Utilization - Storage occurs in deep saline aquifers, depleted oil fields, and unmineable coal seams. Utilization includes EOR, chemical synthesis, and mineralization. CCUS is considered essential for decarbonizing hard-to-abate sectors like oil and gas, but its commercial deployment remains limited due to cost and operational complexities [8].

2.2. Challenges of Traditional CCUS Systems

Although CCUS has been technically validated, it faces significant barriers that limit its widespread deployment: High Energy and Operational Costs - CO_2 capture, especially in post-combustion systems, is energy-intensive and can reduce the overall efficiency of oil and gas operations [9]. System Complexity and Inefficiency -Traditional models used for designing and operating CCUS systems are often static and deterministic, lacking the adaptability required to deal with dynamic real-world conditions [10]. Leakage and Long-Term Storage Risks: Ensuring the integrity of CO_2 storage over decades is challenging. The risk of leakage due to faults or poor cap rock integrity can compromise environmental safety [11]. Monitoring and Verification Limitations: Traditional monitoring relies on expensive geophysical surveys and limited well data, which can be slow and incomplete [12]. Regulatory and Social Barriers: Regulatory uncertainty and community opposition to underground storage projects can delay or prevent implementation [13]. These limitations have created a demand for smarter, more adaptable solutions that can optimize CCUS performance in real-time; this is where AI comes in.

2.3. Emergence of AI in Industrial Optimization

Artificial Intelligence, particularly machine learning (ML), deep learning (DL), and reinforcement learning (RL), has demonstrated the ability to revolutionize industrial process optimization. In the oil and gas industry, AI is already being used for predictive maintenance, real-time drilling analytics, production forecasting, and anomaly detection [14].

Table 1 Comparative review of relevant literatures

Papers References	Objectives	Results	Findings	Practical Implications
[18]	• Explore AI's role in enhancing CCS supply chains. • Assess impact on supplier quality and operational efficiency.	• AI enhances carbon capture efficiency and supplier quality. • Predictive analytics improve decision-making and risk management.	• AI-driven systems enhance carbon capture efficiency significantly. • Improved supplier management reduces emissions and operational costs.	• AI optimizes CCS supply chains and reduces costs. • Enhances supplier quality and carbon capture efficiency.
[19]	• Synthesize CCUS elements over 50 years for emission reduction. • Evaluate carbon capture techniques and their economic feasibility.	• Evaluates CCUS technologies' mitigation potential for global emissions. • Highlights economic feasibility and environmental impact of various techniques.	• Evaluates CCUS techniques' mitigation potential and economic feasibility. • Highlights integration of CCUS in climate strategies for net-zero emissions.	• Evaluates CCUS techniques for global emission reduction potential. • Highlights economic feasibility and environmental impact of CCUS technologies.
[20]	• Systematic review of machine learning in CCUS applications. • Identify pathways for advancing CCUS commercialization and research.	• ML enhances CCUS knowledge and deployment across value chain. • Recommendations for further research to develop ML role in CCUS.	• Machine learning enhances CCUS efficiency and cost-effectiveness. • Systematic review accelerates CCUS commercialization and research expansion.	• ML can accelerate research in CO2 capture. • ML is applied in adsorbent synthesis and characterisation.
[21]	• Summarize AI advancements in nanomaterials discovery. • Discuss limitations and future research directions for AI applications.	• AI accelerates nanomaterials discovery for clean energy. • AI aids in CO2 capture and conversion materials.	• AI accelerates nanomaterials discovery for clean energy technologies. • Identifies challenges and future directions for AI in nanomaterials.	• Accelerates nanomaterial discovery for clean energy and carbon capture technologies. • Enhances AI applications in material research for sustainable energy solutions.
[22]	• Focus on AI integration with carbon capture technology. • Optimize carbon capture processes and minimize CO2 emissions.	• AI enhances efficiency in carbon capture technologies. • Optimizes CO2 injection processes and minimizes emissions.	• AI enhances efficiency in carbon capture technology operations. • AI optimizes injection processes and minimizes CO2 emissions.	• AI enhances efficiency in carbon capture technologies. • Optimizes CO2 injection processes and reduces emissions.

[23]	• Enhance carbon capture efficiency using AI automation. • Improve predictive maintenance in oil and gas facilities.	• AI automation enhances carbon capture efficiency and maintenance. • Improved CO2 sequestration rates with minimized operational interruptions.	• AI automation enhances carbon capture efficiency and predictive maintenance. • Real-life examples show successful AI integration in CCS.	• Enhances carbon capture efficiency in oil and gas facilities. • Improves predictive maintenance through AI-driven automation processes.
[24]	• Integrate digital technology and AI in CCUS monitoring. • Enhance efficiency, safety, and reliability in CCUS operations.	• Enhanced monitoring and anomaly detection in CCUS systems. • Optimized performance through AI-driven predictive maintenance.	• Advanced sensing integrates nano sensing, IoT, and AI technologies. • Enhances CCUS efficiency, safety, and reliability through real-time monitoring.	• Enhances real-time monitoring and anomaly detection in CCUS. • Optimizes system performance through AI-driven predictive maintenance.
[25]	• Optimize post-combustion CO2 capture using AI techniques. • Identify critical factors affecting CO2 capture efficiency.	• CNN models relationships in C02 capture process efficiently. • Bayesian networks identify critical factors for optimizing C02 capture levels.	• Optimized CO2 capture using AI-enabled CNN and Bayesian networks. • Identified critical factors affecting CO2 capture efficiency.	• Optimizes CO2 capture efficiency using AI techniques. • Supports carbon neutrality goals through enhanced CCUS processes.
[26]	• Develop a robust hybrid assessment tool for CCUS. • Optimize CCUS systems design and operation costs.	• Identified need for robust hybrid assessment tool for CCUS. • Proposed AI methods to optimize CCUS design and operation.	• Need for robust hybrid assessment tool for CCUS. • AI methods can optimize CCUS design and operation.	• AI optimizes CCUS design and operation costs. • AI methods accelerate materials selection and process optimization.
[27]	• Optimize carbon capture and storage processes in oil and gas. • Identify optimal geological formations for carbon storage.	• Optimized carbon storage using data science and geological insights. • Addressed challenges in data heterogeneity and geological complexity.	• Integrates data science with geological insights for CCS optimization. • Identifies optimal formations and predicts sequestration capacities.	• Optimizes carbon capture and storage processes in oil and gas. • Identifies optimal geological formations for carbon storage.
[28]	• Evaluate CO2 work capacity and MOF selectivity predictions. • Optimize machine learning methodologies for CO2/N2 analysis.	• Mean absolute errors for CO2/N2 selectivity: 25 and 0.8 mmol/g. • Negative correlation between CO2 capacity and chemical makeup.	• Neural network model predicts CO2/N2 selectivity accurately. • Pore size and surface area affect gas absorbability.	• Enhances CO2 capture efficiency using machine learning models. • Improves predictability of MOF characteristics for CO2/N2 selectivity.

[29]	• Optimize CO_2 removal from flue gas using RL. • Minimize operating energy in carbon capture applications.	• Lower energy costs achieved in over 70% of cases. • Evaluation of RL method for CO_2 capture process optimizations presented.	• RL algorithm reduces energy costs in over 70% of cases. • Optimizes CO_2 removal from flue gas effectively.	• Optimizes CO_2 removal with lower energy costs. • Enhances AI implementation in oil and gas industries.
[30]	• Highlight integration of AI and CDR technology. • Improve efficiency and reduce environmental impact.	• Highlights integration of AI and CDR for energy optimization. • Suggests future research directions for improved efficiency and viability.	• Integration of AI enhances CDR technology effectiveness. • Future research focuses on efficiency and economic viability.	• Enhances energy efficiency and reduces environmental impact. • Promotes interdisciplinary collaboration for effective policy frameworks.
[31]	• Enhance CO_2 solubility using AI and optimization techniques. • Develop cost-efficient carbon capture and storage methods.	• ANFIS model outperforms ANOVA in CO_2 solubility prediction. • IGWO optimization increases CO_2 solubility by 13.4%.	• ANFIS model outperforms traditional ANOVA in CO_2 solubility prediction. • IGWO optimizes parameters, increasing CO_2 solubility by 13.4%.	• Enhances CO_2 solubility for effective carbon capture. • Promotes sustainable energy and environmental sustainability solutions.
[32]	• Develop geologically realistic heterogeneous reservoir models using AI. • Optimize CO_2 storage efficiency and predict plume migration behavior.	• Developed AI-based 3D geologic models for CO_2 sequestration. • Enhanced geological heterogeneity characterization reduces project uncertainty.	• Developed AI-based geologic modeling for CO_2 sequestration. • Enhanced geological heterogeneity characterization improves CO_2 storage efficiency.	• Enhanced CO_2 plume migration predictions and optimization. • Improved geological heterogeneity characterization for CO_2 storage efficiency.
[33]	• Evaluate new emissions monitoring technologies for deployment in Oman. • Support AI/MoS as part of emissions monitoring portfolio.	• AI/MoS-based technologies effectively monitor emissions in extreme conditions. • Valuable data supports continuous emissions monitoring in Oil & Gas.	• AI/MoS technologies effectively monitor emissions in extreme conditions. • Continuous monitoring enhances data quality and completeness.	• AI/MoS technologies improve emissions monitoring effectiveness and cost. • Supports decarbonization efforts in Oil & Gas industry.
[34]	• Analyze AI applications in oil and gas projects • Provide recommendations for sustainable development in the industry	• Positive trend in AI research related to oil and gas construction projects • Insight into promising AI applications and methodologies	• Positive trend in AI research since 2016. • AI enhances sustainability in oil and gas projects.	• Improved research on AI applications in oil and gas projects after 2018. • AI can improve construction work and project efficiency in oil and gas projects.

		for sustainable development in the industry		
[35]	• Explore AI integration in oil and gas sustainability. • Examine optimization techniques for production process efficiency.	• AI optimizes oil production for sustainability, efficiency, and profitability. • Case studies show reduced emissions, water usage, and operational risks.	• AI optimizes oil and gas production for sustainability. • Enhances efficiency, reduces environmental impact, and maximizes resource recovery.	• Enhances sustainability in oil and gas production processes. • Reduces environmental impact and operational risks.
[36]	• Evaluate effectiveness of IT solutions for emission reduction. • Analyze real-world implementations and their impact on emissions.	• Advanced IT solutions show promise for emission reduction in oil/gas. • IoT, AI, Big Data aid in emissions tracking and optimization.	• Advanced IT solutions show promise for emission reduction in oil industry. • IoT, AI, and Big Data analytics aid in emissions management.	• Advanced IT solutions reduce emissions in oil and gas sector. • Real-time monitoring, predictive maintenance, emissions tracking, and reporting benefits.
[37]	• Examine IoT-enabled CCS for Enhanced Oil Recovery. • Optimize carbon capture efficiency and reduce emissions.	• IoT enhances CCS efficiency and sustainability in EOR. • Promotes carbon-neutral oil and gas operations.	• IoT enhances carbon capture efficiency and reduces costs. • Enables carbon-neutral oil and gas operations through real-time monitoring.	• Optimizes carbon capture efficiency and lowers operating costs. • Enhances environmental sustainability through remote monitoring and predictive maintenance.

AI excels in: Handling large volumes of structured and unstructured data, identifying hidden patterns and correlations, Making fast, accurate predictions under uncertainty [15]. In the context of CCUS, AI can help build predictive models for CO_2 behavior in storage formations, optimize process control in capture systems, detect leaks in pipelines, and reduce energy consumption during compression and transport. The versatility and learning capability of AI make it a valuable tool for addressing the multifaceted challenges of CCUS, especially in achieving higher efficiency and reliability [16].

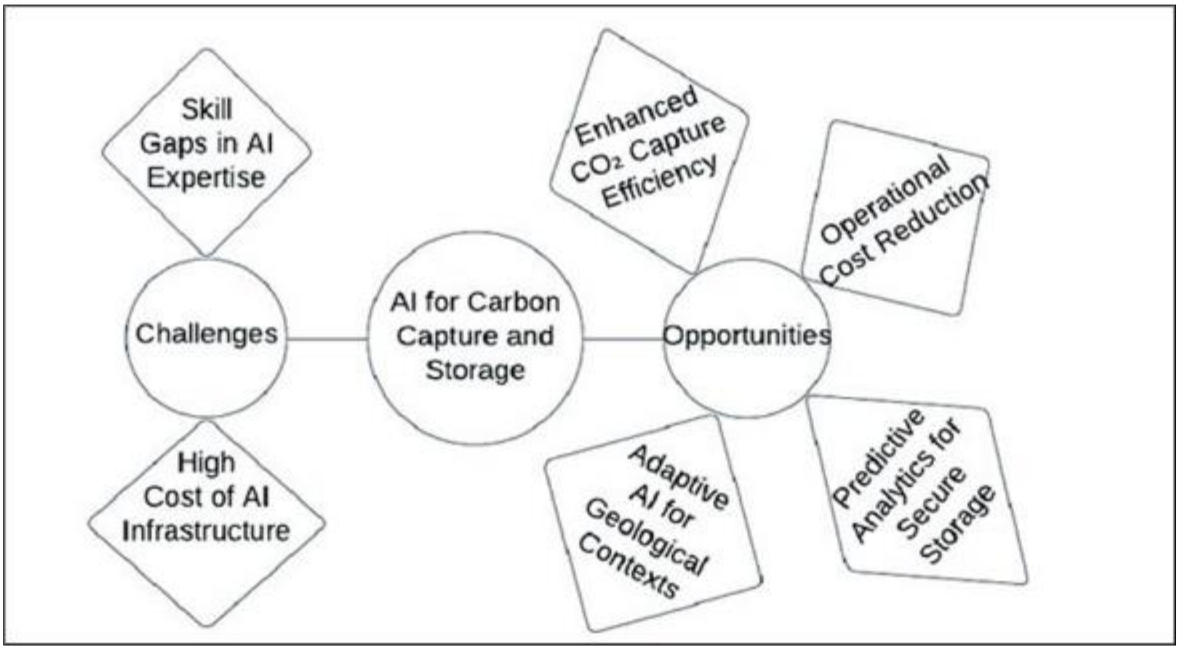

Figure 1 Challenges and Opportunities in Scaling Artificial Intelligence for Carbon Capture and Storage [17]

3. Discussion

3.1. AI in CO_2 Capture Optimization

CO_2 capture, particularly post-combustion capture using chemical solvents, is the most energy-intensive and cost-defining component of CCUS. AI has the potential to significantly optimize this process. Machine learning algorithms such as artificial neural networks (ANNs), support vector machines (SVMs), and decision trees are increasingly being employed to model and predict CO_2 capture efficiency under varying operational conditions. These models enable adaptive control strategies that can dynamically adjust solvent flow rates, temperature, and pressure based on real-time process data, leading to substantial energy savings and operational efficiency (Zhou et al., 2021). Moreover, AI is being integrated with process simulators to develop digital twins of capture plants which are virtual replicas that continuously learn from real-time data and predict future performance. These AI-powered digital twins can identify operational anomalies, forecast degradation in solvent performance, and suggest preventive measures, thus reducing downtime and maintenance costs. In addition, AI is aiding the discovery of novel capture materials (e.g., metal-organic frameworks) through high-throughput screening and molecular simulation techniques, accelerating the innovation cycle.

3.2. AI in CO_2 Transportation and Compression

Transporting captured CO_2 through pipelines or other means introduces additional challenges such as pressure optimization, leakage detection, and route selection. AI-based predictive models can forecast pipeline flow behavior, pressure drops, and temperature variations using historical and real-time data. These predictions help optimize compressor operations to ensure efficient CO_2 flow with minimal energy input. Furthermore, AI is revolutionizing leak detection systems by analyzing sensor and acoustic emission data to detect anomalies that may signal pipeline rupture or leakage. Techniques such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) have been applied to time-series data from distributed fiber optic sensors and smart pigging tools, significantly improving the accuracy and speed of fault detection.

Geospatial AI tools are also being used for optimal CO_2 transport routing, taking into account environmental constraints, population density, terrain complexity, and cost factors enhancing safety and economic efficiency simultaneously.

3.3. AI in CO_2 Storage Monitoring and Risk Assessment

Ensuring the long-term integrity of geological storage sites is essential for the credibility of CCUS. Traditional monitoring approaches are often reactive and limited in spatial-temporal resolution. AI introduces a proactive paradigm by enabling predictive analytics and pattern recognition in large geophysical, geochemical, and sensor datasets. AI algorithms can process seismic survey data to identify caprock integrity, track plume migration, and detect early signs of leakage. For example, unsupervised learning methods such as clustering and principal component analysis (PCA) have been used to detect abnormal shifts in seismic signals without prior labeling. AI can also fuse data from multiple monitoring tools like pressure sensors, gas composition analyzers, and satellite imagery to provide a holistic and real-time understanding of storage site behavior. Moreover, probabilistic AI models support quantitative risk assessments by simulating different leakage scenarios and estimating the likelihood of their occurrence, allowing operators to develop preemptive mitigation strategies and ensure regulatory compliance.

3.4. AI for CO_2 Utilization in Enhanced Oil Recovery (EOR)

In CO_2-EOR, accurate reservoir modeling and real-time decision-making are crucial to optimize both oil recovery and CO_2 sequestration. AI models trained on historical production and injection data can predict reservoir responses to CO_2 injection under various operational scenarios. These models can guide optimal well placement, injection rates, and scheduling strategies to maximize recovery and minimize CO_2 breakthrough. In addition, AI enhances compositional simulation by learning complex phase behavior relationships from experimental data, reducing the need for extensive physical measurements. Coupling AI with reservoir simulators allows for faster history matching, reducing the time and effort required in calibrating geological models to match observed data. AI also supports adaptive optimization of surfactant and solvent injection in EOR processes, helping to balance performance and economic returns.

3.5. Barriers to AI-CCUS Integration

Despite its transformative potential, the integration of AI into CCUS in oil and gas is not without challenges. These include; Data Scarcity and Quality - AI models require large volumes of high-quality data. In many cases, CCUS projects are relatively new, and historical data are limited or siloed. Model Transparency and Interpretability - Complex AI models, particularly deep learning networks, often function as “black boxes,” making it difficult for engineers to interpret their decisions, this affects trust and regulatory acceptance. Cybersecurity and Infrastructure - Digitalization introduces new vulnerabilities. Secure data transfer, storage, and AI model protection are crucial for widespread adoption. Interdisciplinary Gaps - Successful AI-CCUS integration requires collaboration between data scientists, petroleum engineers, geologists, and environmental experts, an alignment that is still evolving in many organizations. These challenges highlight the need for standardized frameworks, open-access datasets, and regulatory guidelines that can foster innovation while ensuring safety, transparency, and accountability.

4. Conclusion

The integration of Artificial Intelligence (AI) into Carbon Capture, Utilization, and Storage (CCUS) systems represents a transformative opportunity for the oil and gas industry to achieve its environmental sustainability goals. As global pressure mounts for carbon neutrality, CCUS remains a pivotal strategy for mitigating CO_2 emissions from fossil fuel operations. However, traditional CCUS systems are limited by high costs, complex process dynamics, and significant risks associated with long-term CO_2 storage. AI offers a novel and data-driven approach to overcoming these challenges by enabling real-time monitoring, dynamic optimization, and predictive maintenance across the entire CCUS value chain. This review highlights that AI applications in CO_2 capture can significantly reduce energy consumption and improve process efficiency through advanced modeling and control strategies. In transportation and compression, AI enhances pipeline integrity management and flow optimization, contributing to safer and more cost-effective CO_2 logistics. AI's impact on geological storage is especially critical through seismic analysis, risk forecasting, and multi-sensor data fusion, AI improves the reliability of long-term storage monitoring. Furthermore, in CO_2-EOR, AI supports reservoir modeling, injection optimization, and production forecasting, improving both economic returns and sequestration effectiveness. Despite its benefits, the adoption of AI in CCUS is still in its early stages. Challenges such as data availability, model transparency, interdisciplinary skill gaps, and cybersecurity concerns must be addressed to facilitate large-scale implementation. Nevertheless, with continued research, regulatory support, and industry collaboration, AI-driven CCUS solutions hold immense potential to accelerate decarbonization in the oil and gas sector. In conclusion, the synergy between AI and CCUS not only enhances operational efficiency but also strengthens the industry's ability to meet climate targets. As digital technologies mature and CCUS projects scale up, integrating AI into these systems will be a critical enabler for a low-carbon, sustainable future in the oil and gas industry.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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