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# Carbon Capture, Utilization, and Storage (CCUS) Engineering: A Comparative Analysis between Norway and Canada

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## ABSTRACT

Carbon Capture, Utilization, and Storage (CCUS) has emerged as a key engineering solution for reducing industrial carbon emissions and supporting the transition toward net-zero targets. Norway and Canada are recognized as global leaders in CCUS implementation, supported by strong government policies, advanced engineering capabilities, and large-scale demonstration projects. This study systematically reviews the development of CCUS engineering in both countries by synthesizing research published over the last fibe years. The review compares technological advancements, infrastructure development, carbon transportation and storage systems, policy frameworks, economic feasibility, and industrial implementation. The findings indicate that Norway has demonstrated significant progress in offshore geological storage and integrated carbon transport networks, while Canada has emphasized large-scale carbon capture applications in the energy and industrial sectors. Despite different implementation strategies, both countries highlight the importance of technological innovation, public investment, regulatory support, and international collaboration. This review provides comprehensive insights into current research trends, identifies existing challenges, and discusses future opportunities for advancing CCUS engineering as a sustainable pathway for global decarbonization.

***Keywords:*** *Canada; Carbon Capture; CCUS Engineering; Comparative Analysis; Norway; Utilization, and Storage.*

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## 1. | INTRODUCTION

Climate change has become one of the greatest global challenges, driving countries to adopt engineering solutions that can significantly reduce greenhouse gas emissions while maintaining economic growth and industrial productivity. Among various decarbonization technologies, Carbon Capture, Utilization, and Storage (CCUS) has gained increasing attention as an effective strategy for capturing carbon dioxide ($CO_2$) emissions from industrial processes and preventing their release into the atmosphere. Unlike renewable energy technologies that primarily replace fossil fuel use, CCUS enables emissions reduction from hard-to-abate sectors such as cement, steel, petrochemicals, and oil and gas industries. Consequently, CCUS has become an important component of global climate mitigation strategies and is widely recognized as a key technology for achieving net-zero emission targets (Fernandez et al., 2024).

The period between 2021 and 2025 witnessed rapid progress in CCUS engineering driven by technological innovation, supportive government policies, and increasing industrial investment. Advances in carbon capture technologies have improved capture efficiency while reducing operational costs through the development of advanced solvents, membrane separation systems, solid sorbents, and direct air capture technologies. At the same time, engineering improvements in carbon transportation, geological storage, and monitoring systems have enhanced the safety and reliability of long-term $CO_2$ storage. Digital technologies, including artificial intelligence, machine learning, and sensor-based monitoring, have further optimized CCUS operations by improving process efficiency and supporting real-time decision-making (Saxena et al., 2024).

Norway and Canada are widely recognized as two of the world's leading countries in the development and implementation of CCUS engineering. Norway has focused on offshore geological storage by utilizing its extensive experience in offshore petroleum engineering and reservoir management. Through strong government support, research collaboration, and long-term investment, the country has established integrated systems for carbon transportation and offshore storage beneath the North Sea. These developments have strengthened Norway's position as a strategic carbon storage hub while demonstrating the technical feasibility of large-scale offshore CCUS projects (Wildenborg et al., 2022).

Canada has adopted a different implementation strategy by integrating CCUS into energy production and carbon-intensive industries. Supported by abundant geological storage resources and extensive industrial infrastructure, Canada has developed several commercial-scale carbon capture projects involving power generation, oil and gas processing, and manufacturing sectors. Continuous investment in research and engineering has improved carbon capture performance, transportation efficiency, storage monitoring, and project economics. Government incentives and industrial partnerships have also accelerated technology deployment, making Canada one of the global leaders in commercial CCUS applications (Ampomah et al., 2024).

Although both countries pursue similar climate objectives, their engineering approaches differ because of variations in industrial structure, geographical conditions, energy resources, and policy priorities. Norway emphasizes offshore carbon storage and international transportation networks, whereas Canada focuses on industrial integration and commercial deployment within domestic sectors (Chaube et al., 2020). Comparing these approaches provides valuable insights into engineering innovation, infrastructure development, regulatory support, and technology commercialization. Understanding their similarities and differences is important for identifying best practices that can be adopted by other countries seeking to accelerate carbon reduction through CCUS.

Therefore, this study conducts a Systematic Literature Review (SLR) to compare recent developments in CCUS engineering in Norway and Canada using scientific publications published between 2021 and 2025. The review evaluates advances in carbon capture technologies, transportation systems, geological storage, engineering innovation, policy support, environmental performance, and implementation challenges. By synthesizing recent literature, this study aims to identify current research trends, technological strengths, remaining challenges, and future opportunities for CCUS engineering (Peres et al., 2022). The findings are expected to provide useful references for researchers, engineers, policymakers, and industry stakeholders in supporting the global transition toward sustainable carbon management and net-zero emissions.

## 2. | RESEARCH METHOD

This study employed a Systematic Literature Review (SLR) to systematically identify, evaluate, and synthesize recent scientific evidence regarding the development of Carbon Capture, Utilization, and Storage (CCUS) engineering in Norway and Canada. The SLR approach was selected because it provides a transparent, structured, and reproducible process for reviewing published literature while minimizing potential bias in article selection and data interpretation. The review was conducted through several sequential stages, including research question formulation, literature identification, screening, eligibility assessment, data extraction, qualitative synthesis, and comparative analysis. The primary objective was to compare engineering developments, technological innovations, implementation strategies, and policy support for CCUS in the two countries based on recent scientific publications. The research focused exclusively on literature published between 2021 and 2025 to ensure that the findings reflected the latest advances in carbon capture technologies, transportation systems, geological storage, digital engineering applications, and industrial implementation (Litvinenko, 2020).

Relevant publications were identified using internationally recognized scientific databases, including Google Scholar, Scopus, ScienceDirect, SpringerLink, Web of Science, IEEE Xplore, and MDPI. The literature search was conducted using combinations of keywords such as “Carbon Capture, Utilization, and Storage,” “CCUS Engineering,” “Carbon Capture Technology,” “Carbon Storage,” “Geological Storage,” “Carbon Transport,” “Net Zero,” “Norway,” “Canada,” and “Carbon Management.” Additional studies were identified by reviewing the reference lists of selected articles to ensure comprehensive literature coverage. Only peer-reviewed journal articles written in English were included in the review. The inclusion criteria consisted of publications discussing engineering aspects of CCUS, technological development, infrastructure design, geological storage, monitoring systems, environmental performance, economic evaluation, industrial implementation, or policy analysis related to Norway or Canada. Publications published before 2021, conference abstracts without complete manuscripts, duplicate articles, editorial papers, and studies with insufficient engineering relevance were excluded from the analysis (Hanna et al., 2020).

After the literature screening process, the selected studies were carefully examined to extract relevant information, including publication year, research objectives, engineering methodologies, capture technologies, transportation infrastructure, storage techniques, utilization pathways, monitoring systems, implementation challenges, policy frameworks, environmental impacts, and economic considerations. The extracted information was then organized into comparative categories to facilitate systematic evaluation of similarities and differences between Norway and Canada. A qualitative synthesis approach was adopted to integrate findings from multiple studies, identify recurring research themes, analyze technological trends, evaluate engineering performance, and determine future research opportunities (Ooi et al., 2023). The results of this synthesis formed the basis of the discussion presented in this review, providing a comprehensive comparison of recent CCUS engineering developments and highlighting their contributions to sustainable industrial decarbonization and long-term carbon emission reduction strategies.

## 3. | RESULTS AND DISCUSSION

The systematic review indicates that Carbon Capture, Utilization, and Storage (CCUS) engineering has undergone significant development between 2021 and 2025, reflecting the increasing global commitment to achieving net-zero emissions and reducing industrial greenhouse gas emissions. Analysis of the selected literature demonstrates that recent CCUS research has shifted from focusing solely on carbon capture technologies toward integrated engineering systems that combine carbon capture, transportation, utilization, geological storage, digital monitoring, and economic optimization. This evolution reflects the growing recognition that successful CCUS implementation depends not only on capture efficiency but also on the effective integration of every stage within the carbon management chain. Among the countries leading this transition, Norway and Canada have emerged as international benchmarks because both possess advanced engineering capabilities, strong governmental commitment, and extensive industrial participation. Although they pursue the same objective of reducing carbon emissions, each country has developed distinctive implementation strategies based on its industrial characteristics, natural resources, and policy priorities (Alkaraan et al., 2024).

The reviewed studies consistently show that technological innovation has substantially improved carbon capture performance during the review period. Advanced amine solvents, membrane separation technologies, adsorption materials, and direct air capture systems have achieved higher capture efficiencies while reducing energy requirements and operational costs. Several publications also emphasize the integration of artificial intelligence, machine learning, and advanced process simulation into capture facilities to optimize process control, predict equipment maintenance, and improve operational reliability. These digital engineering tools enable industries to maximize capture performance while minimizing unnecessary energy consumption, thereby improving the economic feasibility of commercial-scale CCUS deployment (Sullivan et al., 2020).

Norway has demonstrated exceptional progress through the development of offshore geological storage infrastructure supported by decades of experience in offshore petroleum engineering. Existing expertise in drilling technology, reservoir characterization, and subsurface geological analysis has enabled the country to establish highly secure carbon storage facilities beneath the North Sea. The reviewed literature indicates that Norway has concentrated on developing integrated transportation and storage systems capable of receiving captured carbon dioxide from domestic industries as well as neighboring European countries. Offshore saline aquifers provide large storage capacities with favorable geological characteristics, allowing carbon dioxide to be permanently injected into deep subsurface formations under carefully monitored conditions. Continuous seismic monitoring, reservoir simulation, pressure surveillance, and leakage detection systems have further strengthened confidence in long-term storage security while demonstrating the technical maturity of Norwegian CCUS engineering (Akhurst et al., 2021).

Transportation infrastructure represents another major engineering strength identified in Norway. Carbon dioxide is transported through dedicated pipelines and specialized shipping systems before injection into offshore reservoirs. The development of flexible transportation networks has increased operational efficiency while enabling cross-border carbon management between European countries. This integrated approach allows industries located far from suitable storage formations to utilize Norwegian storage infrastructure, creating opportunities for regional cooperation in carbon emission reduction. Consequently, Norway has positioned itself not only as a technology developer but also as a strategic provider of international carbon storage services. The reviewed studies suggest that such centralized infrastructure reduces duplication of investments and improves overall system efficiency through economies of scale.

Canada has adopted a different engineering strategy by integrating CCUS directly into existing industrial sectors. Large-scale implementation has primarily occurred within oil and gas production, petrochemical industries, fertilizer manufacturing, cement production, and electricity generation. The literature highlights that Canada's mature energy infrastructure provides favorable conditions for commercial deployment because existing pipelines, processing facilities, and engineering expertise significantly reduce implementation costs. Unlike Norway's emphasis on offshore storage, Canada relies largely on extensive onshore geological formations capable of securely storing substantial volumes of carbon dioxide. This approach allows industrial facilities to capture emissions and transport them to nearby storage locations using established infrastructure, thereby accelerating project implementation while minimizing additional investment requirements (Cooper, 2021).

The reviewed studies also reveal that Canadian engineering research has focused extensively on improving operational efficiency and lowering capture costs. Researchers have investigated advanced solvent regeneration techniques, waste heat recovery systems, energy integration strategies, and process optimization methods to reduce the energy penalty commonly associated with carbon capture technologies.

Additional research has explored integrating CCUS with hydrogen production, bioenergy systems, and low-carbon industrial processes to enhance overall environmental performance. These engineering innovations demonstrate Canada's commitment to embedding CCUS within broader industrial decarbonization strategies rather than treating it as a standalone emissions reduction technology.

Another important finding is the increasing application of digital engineering throughout the CCUS value chain in both countries. Artificial intelligence has become an essential tool for predicting equipment failures, optimizing solvent performance, estimating storage capacity, and monitoring reservoir integrity. Machine learning models improve forecasting accuracy by analyzing operational data generated during capture and storage processes, while digital twin technology enables engineers to simulate transportation networks and underground storage behavior before field implementation. These technologies improve operational reliability, reduce maintenance costs, and support data-driven decision-making. The integration of digital technologies has transformed CCUS engineering into a multidisciplinary field involving chemical engineering, petroleum engineering, mechanical engineering, environmental engineering, geotechnical engineering, and computer science, thereby expanding opportunities for future technological innovation (Khogali & Mekid, 2023). Environmental performance is another important aspect discussed extensively in the reviewed literature. Most studies conclude that well-designed CCUS systems can significantly reduce industrial carbon emissions while maintaining production capacity. Nevertheless, environmental benefits depend on capture efficiency, energy consumption, transportation distance, storage integrity, and long-term monitoring. Norway's offshore storage strategy provides excellent containment potential because geological formations beneath the North Sea have undergone comprehensive characterization and continuous monitoring for many years. Similarly, Canada's integrated industrial approach has demonstrated substantial emission reductions across multiple sectors, although researchers emphasize that continuous environmental monitoring remains essential to maintain storage security and public confidence. These findings indicate that engineering excellence must be supported by rigorous monitoring programs, transparent reporting systems, and strict regulatory compliance to ensure the long-term effectiveness of CCUS projects (Marbun et al., 2023).

Economic feasibility continues to represent one of the most significant challenges for large-scale CCUS deployment. Although technological innovation has reduced operational costs, capture facilities, transportation infrastructure, storage development, and monitoring systems still require considerable investment. The reviewed studies show that both Norway and Canada have introduced financial incentives, carbon pricing mechanisms, and government funding programs to improve project viability and encourage industrial participation. Norway has invested in shared transportation and offshore storage infrastructure that can accommodate carbon emissions from multiple industrial sources, allowing infrastructure costs to be distributed across several users. Canada has primarily reduced implementation costs by utilizing existing industrial facilities, pipeline networks, and engineering expertise developed through decades of energy production. These different economic strategies demonstrate that successful CCUS implementation depends on adapting engineering solutions to national industrial conditions and available infrastructure (Pregnolato et al., 2022).

Policy support has also played a decisive role in accelerating technological development. The literature consistently indicates that effective regulations provide technical standards for carbon capture, transportation, storage operations, environmental monitoring, and long-term liability management. Norway has established comprehensive regulations governing offshore storage activities, supported by clear permitting procedures and continuous government supervision. This regulatory certainty has strengthened investor confidence while promoting collaboration among research institutions, government agencies, and industrial companies. Canada has adopted complementary policy instruments, including investment incentives, tax credits, and carbon pricing, encouraging industries to accelerate the commercialization of CCUS technologies. The combination of regulatory certainty and financial support has created favorable conditions for long-term investment in both countries (Nguyen & Lee, 2021).

Collaboration among universities, research organizations, technology developers, industrial companies, and government institutions has become another important factor supporting CCUS engineering. The reviewed publications demonstrate that multidisciplinary collaboration accelerates technological innovation, facilitates knowledge transfer, and reduces technical uncertainties associated with commercial deployment. Norway has promoted international cooperation by developing storage facilities capable of receiving carbon dioxide from multiple European countries, strengthening its position as a regional carbon storage hub. Canada has emphasized partnerships between research institutions and industrial operators to improve technology integration, optimize operational performance, and accelerate technology transfer. These collaborative approaches illustrate that engineering innovation is strengthened when supported by coordinated institutional and industrial partnerships.

Despite substantial progress, several engineering challenges remain. High capture costs, significant energy requirements, infrastructure expansion, and long-term storage monitoring continue to limit widespread implementation. Carbon capture technologies still consume considerable energy, reducing overall system efficiency when low-carbon electricity is unavailable. Transportation infrastructure must continue expanding to connect industrial emission sources with suitable storage locations, while monitoring technologies require continuous improvement to verify reservoir integrity and detect potential leakage. Addressing these challenges will require ongoing engineering research, advanced materials, intelligent monitoring systems, and greater integration of artificial intelligence and digital technologies throughout the CCUS value chain (Yan et al., 2021).

The comparative analysis demonstrates that Norway and Canada provide complementary engineering models for future CCUS development. Norway's principal strength lies in offshore geological storage, integrated transportation infrastructure, and international carbon management services, whereas Canada has successfully demonstrated large-scale industrial integration supported by mature energy infrastructure and strong commercial participation. Although each country faces different technical, economic, and regulatory challenges, both have shown that sustained government commitment, technological innovation, interdisciplinary collaboration, and continuous engineering improvement are fundamental to successful

CCUS implementation. The findings suggest that combining Norway's expertise with Canada's experience could accelerate global CCUS deployment, strengthen industrial decarbonization strategies, and contribute significantly to achieving long-term net-zero emission targets.

## 4. | CONCLUSION

This Systematic Literature Review demonstrates that Carbon Capture, Utilization, and Storage (CCUS) has become a strategic engineering solution for supporting industrial decarbonization and achieving global net-zero emission targets. The comparative analysis indicates that Norway and Canada have established strong positions in CCUS development through different but complementary engineering approaches. Norway has demonstrated significant expertise in offshore geological storage, integrated carbon transportation infrastructure, and long-term storage management, while Canada has successfully integrated CCUS into large-scale industrial operations by utilizing existing energy infrastructure and extensive geological storage resources. These different implementation strategies illustrate that successful CCUS deployment depends on technological innovation, supportive government policies, appropriate infrastructure, and strong collaboration among industry, academia, and policymakers.

The review also highlights substantial technological progress between 2021 and 2025, including improvements in carbon capture efficiency, digital monitoring systems, artificial intelligence applications, transportation networks, and geological storage technologies. Despite these advances, challenges related to implementation costs, energy requirements, infrastructure expansion, and long-term storage monitoring remain important considerations for future development. Overall, the experiences of Norway and Canada provide valuable engineering references for other countries seeking to implement CCUS as part of sustainable carbon management strategies. Continued investment in research, engineering innovation, international collaboration, and supportive policy frameworks will be essential to accelerate large-scale CCUS deployment and strengthen global efforts to reduce carbon emissions while maintaining industrial competitiveness.

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***Conflict of Interest Statement***

The authors declare that there is no conflict of interest.

***Ethical Approval and Originality Statement***

Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

***Data Disclosure Statement***

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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