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Evaluation of Technological Progress, Obstacles, and Resolutions in Carbon Capture and Storage within the Oil and Gas Sector

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Abstract

Carbon Capture and Storage (CCS) technology has surfaced as an indispensable instrument for curbing carbon emissions within the Oil and Gas (O&G) sector, particularly in response to global climate change's escalating concerns. Despite its promising potential, the integration of CCS is confronted with many challenges, encompassing technological impediments, regulatory ambiguities, and public apprehension. This research comprehensively examines the present status, impediments, and prospective solutions of CCS technology within the O&G sector, emphasizing comprehending technological advancements, pinpointing integration barriers, and suggesting strategies for surmounting these obstacles. Employing a mixed-methods approach, this study amalgamates a systematic literature review and theoretical frameworks to appraise CCS integration. Secondary data is collected and meticulously managed to guarantee rigorous analysis and precise representation of findings. The results disclose considerable progress in CCS technology over the past two decades, thereby establishing it as a pivotal contributor to the global climate response. Nevertheless, despite this progress, CCS is still in its nascent stages, capturing merely a fraction of global emissions. Commercial hurdles, regulatory uncertainties, and public skepticism impede widespread adoption, necessitating collaborative and innovative strategies for successful integration. Consequently, this research underscores the significance of interdisciplinary collaboration, innovative methodologies, and stakeholder engagement in propelling CCS deployment within the O&G sector. By addressing technological, regulatory, and societal challenges, CCS can assume a pivotal role in transitioning towards a low-carbon future and accomplishing sustainability objectives.

Keywords

Oil and Gas, Fossil Fuel, Carbon Emissions, Carbon Capture and Storage, Climate Change

1. Introduction

The oil and gas (O&G) business is at the forefront of technological innovation and sustainability due to the growing global energy needs and the pressing need to solve environmental challenges. Delving into the intricacies of this dynamic industry makes it evident that reducing carbon emissions is an imperative task, as the oil and gas (O&G) sector has been a crucial component of the global energy supply for over a century (Yao et al., 2020; Kabeyi & Olanrewaju, 2022). Nevertheless, the environmental impacts of burning fossil fuels, especially regarding carbon emissions, have arisen as a major concern (Yao et al., 2020; Kabeyi & Olanrewaju, 2022). This has stimulated the investigation of Carbon Capture and Storage (CCS) technologies as a probable countermeasure to these emissions (Poothia & Pandey, 2023). While CCS emerges as a hopeful path for shrinking the industry's carbon footprint, the road to its broad implementation is replete with technological hurdles and operational complications (Bui et al., 2021).

The origin of CCS can be traced back to the mid-20th century, when it was initially suggested to decrease greenhouse gas emissions (IEA, 2012). Since then, numerous technological advances have been made (Ma et al., 2022), and a diversity of experimental projects have been introduced globally (Wang, 2020; Veloso et al., 2022). However, current literature on this subject has primarily focused on the technical aspects of CCS, such as capture methods, storage alternatives, and efficiency (Sekera & Lichtenberger, 2020; Nielsen, Stavrianakis, & Morrison, 2022). However, a wealth of all-inclusive studies evaluate the progress of CCS technology within the context of the O&G sector and pinpoint the specific hurdles it encounters. Moreover, while several possible solutions have been proposed, their viability and usefulness remain unclear (OIES, 2022).

Thus, by evaluating the level of CCS technology now, highlighting obstacles, and directing future research and regulation in this area, this study has the potential to further the larger objective of realizing a sustainable energy future. By carefully evaluating the state of CCS technology in the oil and gas industry, identifying the main technological obstacles, assessing the viability and impact of suggested solutions, and offering insightful information to researchers, decision-makers, and industry stakeholders in the fight against carbon emissions, it will close the knowledge gap in the literature.

2. Literature Review

2.1. Historical Literature Review

Understanding the current state of CCS technology in the oil and gas industry and recognizing possible obstacles and solutions requires an understanding of its past development. CCS was first presented as a way to reduce greenhouse gas emissions in the middle of the 20th century (Ma et al., 2022). The oil and gas (O&G) sector has been a major contributor to the world's energy supply for more than a century, but the environmental effects of burning fossil fuels, especially carbon emissions, have caused serious worries (Ma et al., 2022).

Hence, the Paris Agreement of 2015 became a viable instrument, setting the appropriate benchmark to work toward such a goal. The Paris Agreement, which was signed in December 2015 under the auspices of the United Nations Framework Convention on Climate Change (UNFCCC), seeks to keep average global warming well below 2˚C over preindustrial levels (Guiot & Cramer, 2016). Only a 1.5˚C warming scenario allows ecosystems to remain within Holocene variability, while 2˚C or higher would cause unprecedented alterations in Mediterranean land ecosystems (Guiot & Cramer, 2016).

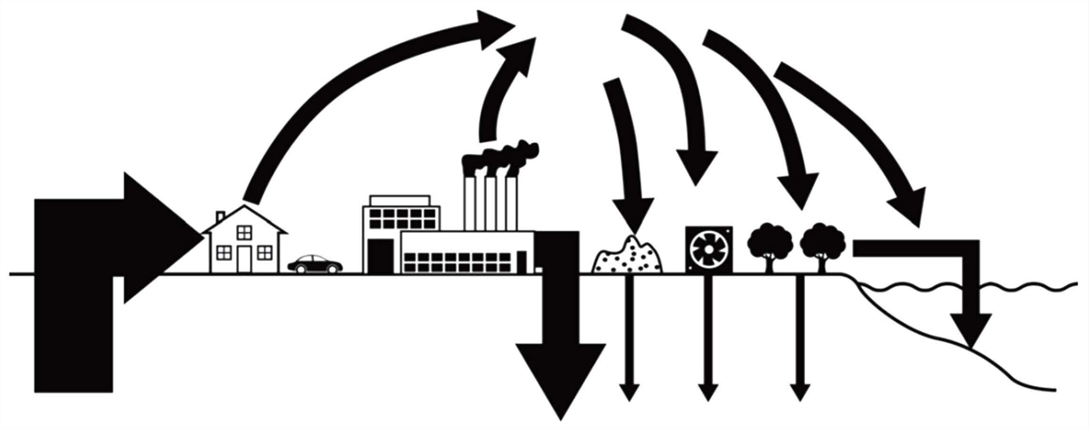

Figure 1. Conceptual pathways of anthropogenic carbon flow are to be managed (Haszeldine et al., 2018).

Large amounts of carbon from coal, oil, and gas are geologically removed from fossil sources and contemporary biomass, as shown when viewing **Figure 1** from the left. Emissions from industry, transportation, and residential and commercial combustion can be significantly reduced using CCS, which captures and stores CO_2 from industrial sites in deep subsurface locations. Negative emission technologies (NETs) such as direct air capture (DAC), bioenergy with CCS (BECCS), and ocean injection can absorb CO_2 already released into the atmosphere (Haszeldine et al., 2018).

Without policy or financial action, no new commercial-scale CCS projects will be developed after the early 2020s, despite current exponential growth in CO_2 capture with high statistical confidence ($R^2 = 0.97$) (**Figure 2**) (Haszeldine et al., 2018).

Even with these advancements in technology, there are still not enough thorough studies evaluating the development of CCS technology, especially in the oil and gas industry (Bui et al., 2018). Hence, the examination of historical literature highlights the critical role played by the oil and gas (O&G) industry in determining the direction of CCS technology and emphasizes the need to fill knowledge gaps about its development and obstacles. The framework for exploring the theoretical and empirical facets of CCS technology in the parts that follow is laid by this historical setting.

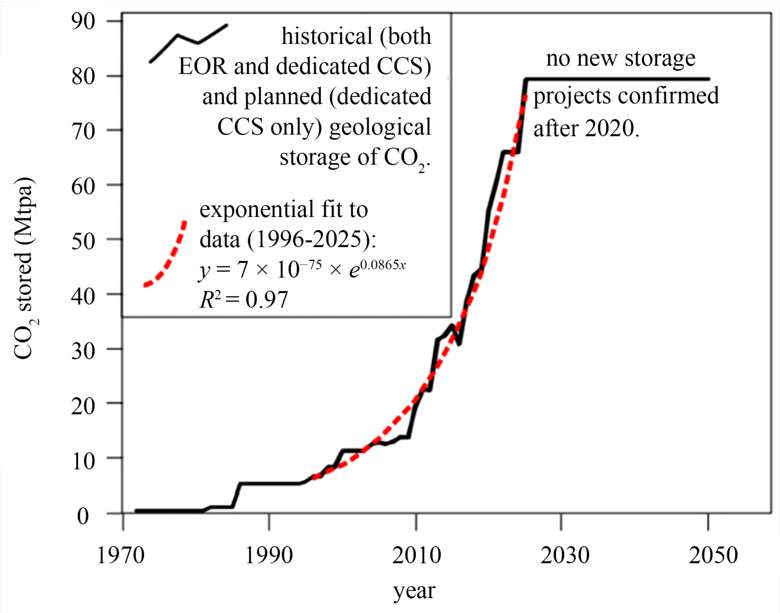

Figure 2. Compilation of past and current CCS projects at industrial scale, showing a continual increase to the present day, but at a rate much slower than planned or politically pledged (Haszeldine et al., 2018).

2.2. Theoretical Review

2.2.1. Theoretical Framework

The O&G industry relies heavily on CCS technology to reduce CO_2 emissions, involving the transportation, capture, and safe underground storage of CO_2 from industrial processes and power generation, as detailed by Bhavsar et al. (2023). This section delves into key theoretical aspects, including the critical role of CCS in heavy oil production and its comprehensive components.

2.2.2. Critical Role in Heavy Oil Industry

The heavy oil sector has acknowledged CCS as a crucial technology, particularly for procedures that include the injection of steam into reservoirs to heat oil and lower its viscosity, thus enabling extraction (Yasemi et al., 2023). According to the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), CCS is crucial for reducing global emissions and meeting climate targets, with the IEA's sustainable development scenario highlighting its importance in achieving net zero by 2050, requiring CCS to store about 5.6 gigatonnes of CO_2 annually. This highlights how important it is theoretically for CCS to reduce related emissions and improve the sustainability of heavy oil production techniques (Page et al., 2020; Kearns, Liu, & Consoli, 2021; Martin-Roberts et al., 2021).

2.2.3. Key Components and Processes

A thorough theoretical understanding of CCS includes its fundamental elements, operations, procedures, carbon storage phases, and associated technologies (Yasemi et al., 2023). This emphasis on theoretical frameworks is essential for academics and business executives who want to understand the improved facts of CCS. Hence, negative emission technologies like direct air capture with CCS (DACCS) and bioenergy with CCS (BECCS) rely on CCS infrastructure to securely isolate millions of tons of CO_2, making it crucial for achieving the UN Paris Agreement's net-zero emissions targets and 100% decarbonization (Harmsen, 2018).

2.2.4. Interim Technology for Emission Reduction

According to theoretical viewpoints, CCS is an emerging technology that is essential for lowering CO_2 emissions from major industrial sources (Bhavsar et al., 2023). The US leads in CCS project development, pioneering CO_2-enhanced oil recovery with CCS (EOR-CCS) technology since the 1970s with the Terrell Natural Gas facility. The necessity of CO_2 for enhanced oil recovery and its price tied to oil prices (~US$70/barrel) drives CCS capacity, increasing profitability during high oil prices (Beck, 2020). According to this view, CCS is a stopgap measure until more permanent, sustainable energy plans are created and put into action.

2.2.5. Framing by the Fossil Fuel Industry

An additional theoretical dimension involves understanding how the fossil fuel industry frames CCS. Drawing from critical theory, the industry is expected to support CCS to address environmental concerns and sustain its operations (Raza et al., 2019). However, CCS technology only reduces emissions related to the extraction of fossil fuels and does not address emissions resulting from the use of fossil fuels. BECCS and DACCS, which are beginning to gain traction in CCS schemes, have the potential to further reduce CO_2 emissions (Martin-Roberts et al., 2021).

Many believe these are essential to reaching net-zero goals and enabling sizable industry clusters to transform from significant sources of emissions into centers of negative emission technologies. This theoretical framework adds a socio-political layer to the discussion, acknowledging the industry's perspective on CCS.

2.2.6. Stabilization of Earth's Climate

According to Raza et al. (2019), the theoretical review highlights that CCS technology involves absorbing and storing CO_2 in deep geological formations, which helps to stabilize the planet's climate. This demonstrates how CCS has wider ecological ramifications and is consistent with international efforts to mitigate climate change (Raza et al., 2019).

2.3. Empirical Review

The empirical literature evaluation of CCS technology is the main topic of the third section. It looks at field studies, practical applications, and real-world implications within the O&G industry, highlighting advancements, difficulties, and prospective solutions based on actual implementation experiences. For example, the largest international oil and gas firms recognize the need to quickly decarbonize in response to government, stakeholder, and environmental demands. As major greenhouse gas producers, their unique technological and economic position makes CCS development advantageous. Some large European firms, like Shell and ENI, have set ambitious net-zero targets (NZT) for 2050, aiming to reduce operational and Scope 3 (the direct emissions from energy products sold to customers) emissions, aligning with the Intergovernmental Panel on Climate Change (IPCC) 2˚C scenario (TPI, 2020). These empirical studies furnish invaluable insights into the practical dynamics of CCS implementation and the challenges faced in preserving the integrity and containment of injected CO_2 within geological formations.

Empirical literature highlights high-throughput synthetic methods for producing zeolitic imidazolate frameworks (ZIFs) for CO_2 capture (Phan et al., 2010), demonstrating the feasibility and scalability of novel materials. Additionally, studies on integrating biofuels with CCS in the marine sector reveal practical implications and technical considerations for reducing emissions (Mukherjee, Bruijnincx, & Junginger, 2020). The empirical literature assessment on CCS technology provides a thorough understanding of its prospects, challenges, and real-world applications, forming the basis for evaluating practical developments, obstacles, and potential solutions in the oil and gas industry.

2.4. Significance of the Literature Review to the Research

The review explores the historical development of CCS technology in the oil and gas industry from the mid-1900s (Ma et al., 2022), highlighting advancements and pilot projects that established CCS as a viable solution to environmental concerns (Yasemi et al., 2023). Most current literature focuses on technical aspects, lacking comprehensive evaluations of CCS progress in the industry (IEA, 2023a). This historical background is crucial for examining the theoretical and empirical elements of CCS in later thesis sections.

3. Research Methodology

3.1. Research Approach and Design

3.1.1. Research Design

To assess technological advancements, challenges, and solutions in CCS within the O&G industry, a secondary research methodology was used. A thorough assessment of the most recent research on CCS technology was part of the research design, with an emphasis on the technology's development, recent developments, difficulties, and prospective solutions in the oil and gas industry. This design entails a methodical and meticulous procedure for locating, gathering, and evaluating pertinent material on the selected subject. Since it enables a thorough analysis of the current state of knowledge, highlights knowledge gaps, and synthesizes findings to inform the study's broader goals and objectives, a systematic literature review is especially appropriate for this kind of research (Brereton et al., 2007). The review will thoroughly examine the advancements, difficulties, and solutions related to CCS in the O&G industry using both qualitative and quantitative data. Qualitative data will offer a profound understanding of context and theoretical frameworks. Quantitative data, on the other hand, will provide quantifiable proof of trends and patterns. A thorough comprehension of the subject will be ensured by this well-rounded approach (Creswell & Creswell, 2017).

3.1.2. Research Philosophy

This study is grounded in interpretivism as its research philosophy (Mertens, 2014). This research, which aims to interpret and comprehend the complex dynamics of technological advancement, problems, and solutions in the context of CCS within the O&G industry, is in line with interpretivism. A detailed grasp of the many facets of CCS technology is made possible by the interpretative approach, which critically reviews and synthesizes the body of available material (Mertens, 2014).

3.1.3. Rationale for Research Design

The capacity to present a comprehensive summary of the topic, including insights into the theoretical underpinnings, historical background, and empirical data pertaining to CCS technology, justifies the use of a systematic literature review design (Tranfield, Denyer, & Smart, 2003). This design integrates different viewpoints and findings from multiple sources to conduct a thorough exploration of the body of existing knowledge.

3.1.4. Limitations of the Research Design

There are certain limits to the research design. First of all, it is dependent on the body of prior research, which limits the production of fresh empirical data. But a secondary research approach by its very nature has this constraint. Second, the chosen literature could have inherent biases from the original research. In an attempt to lessen this, literature from a variety of sources and viewpoints was chosen (Webster & Watson, 2002).

3.2. Research Sampling and Description and Sources of Secondary Data Collected

3.2.1. Research Sampling and Description

Research sampling is not the same as typical empirical research in the context of a systematic literature review. Rather than choosing individuals, the emphasis is on methodically finding and analyzing pertinent material. To make sure the literature selected complies with the study goals, the sampling procedure includes establishing inclusion and exclusion criteria(Webster & Watson, 2002).

Literature that is specifically relevant to CCS technology in the oil and gas industry, with a focus on peer-reviewed academic publications, is included in this study. Outdated publications, non-peer-reviewed or unreliable sources that compromise credibility and dependability, as well as materials that do not advance CCS understanding, are not.

3.2.2. Sampling Procedure and Methodological Steps

The research sample process started with a thorough and methodical search using targeted keywords like “Carbon Capture and Storage”, “Oil and Gas Sector”, and

"CCS technology challenges" across academic databases, scholarly journals, and reliable sources. To view all possible keyword combinations. Keywords and phrases linked to CCS technology, advancements, challenges, and solutions in the oil and gas industry were incorporated into the search strategy. To find other sources, the snowballing method was also employed. These procedures used both modern and historical literature to summarize the development of CCS technology. Following the search, the included and excluded criteria were used to analyze the found literature. A rigorous selection procedure made sure that the selected sources matched the goals of the study and provided insightful information about the advancements, challenges, and solutions in technology related to CCS in the oil and gas industry. Figure 3 provides the entire process.

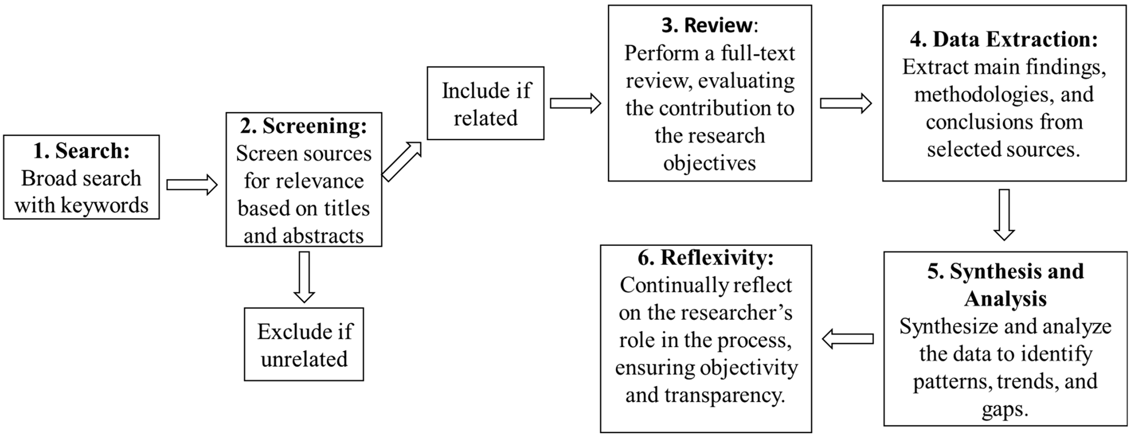

Figure 3. Sampling procedure and methodological steps used in this work.

As previously mentioned, unrelated documents were eliminated during the relevancy screening process, which was based on the document titles and abstracts. A full-text review was conducted on the remaining sources to assess how well they contributed to the goals of the study. The primary results, approaches, and conclusions were taken from the chosen sources. After that, this data was combined and examined to find trends, gaps, and patterns. The role of the researcher in ensuring objectivity and transparency was continuously considered throughout the process.

3.2.3. Sources of Secondary Data Collected

The secondary data sources included a broad spectrum of easily accessible or openly available materials, such as peer-reviewed academic articles and conference proceedings, as well as grey literature (technical reports, industry reports, policy documents, and other documents from the GCCSI, the EU, the US government, and the IEA, among others). Comprehensive searches of the websites of the organizations/institutions, ScienceDirect, JSTOR, Xplore, Google Scholar, and the Google search engine were used to find these sources.

3.3. Quality of Secondary Data

The study evaluated the secondary data for completeness, timeliness, accuracy, reliability, relevance, and potential bias. Recent, peer-reviewed publications, credible books, and studies from renowned international organizations that were specifically connected to CCS technology in the oil and gas industry were given preference. The accuracy and comprehensiveness of the data were evaluated through cross-checking. Potential biases were recognized and taken into consideration, guaranteeing high-quality data for solid and trustworthy research conclusions.

3.4. Secondary Data Ethical Measures

Several ethical guidelines were used to handle and evaluate secondary data in the study "Evaluation of Technological Progress, Obstacles, and Resolutions in Carbon Capture and Storage within the Oil and Gas Sector". To uphold academic integrity, protect intellectual property rights, and preserve openness, all sources were duly credited and acknowledged. Anonymizing data that could be used to identify specific people or organizations helped to protect data privacy. By providing the data exactly as it was discovered in the source, without modification, the integrity of the data was maintained. A balanced perspective of CCS technology in the oil and gas industry was presented, with an emphasis on avoiding bias and misrepresentation and presenting the facts objectively. The transparent description of the research methods, which encompassed the systematic literature review, enhanced the credibility and dependability of the findings. These steps guaranteed the ethical, polite, and responsible use of secondary data.

4. Results/Findings

4.1. Introduction to Results Section

The data was collected to evaluate the technological progress, challenges, and solutions in CCS in the O&G sector, using a mixed methods approach, systematic literature review, and ethical handling of secondary data.

4.2. Technological Progress in CCS in the O&G Sector

Over the past two decades, considerable strides have been made in CCS technologies, positioning them as crucial players in the global climate response, particularly after the Paris Agreement ratification (IEA, 2016). This necessity extends to achieving "negative emissions" in the latter half of the century, aligning with the ambitious objectives outlined in the Paris Agreement (IEA, 2016).

Industry analogs were utilized by the International Energy Agency's Greenhouse Gas (IEAGHG) R&D Program to determine the viability of the build-out rates needed for CCS implementation (Martin-Roberts et al., 2021). They took into account the logistics of five aspects of CCS that required accelerated implementation, estimating that 75 - 150 new global capture facilities would be needed annually. These included the commissioning of new capture facilities, the availability of CO_2 compressors, the creation of CO_2 transport networks (pipelines and CO_2 tanker ships), the development of CO_2 geological storage sites, and the deployment of drilling rigs and the installation of platforms and well pads (**Table 1**).

Table 1. IEAGHG R&D assessment of required build-out rates for CCS deployment (Martin-Roberts et al., 2021).

Resource Being Assessed	Amount of Resources Needed	Industry Comparison	Feasibility
Commissioning of New Capture Facilities	75 - 100 new capture plants/year (worldwide) would be required	Historic commissioning rates of combined cycle gas turbines (CCGT) (global CCGT build-out peaked in the early 2000s, commissioning more than 70 new plants/year between 2000 and 2005, with a maximum of 119 plants/year in 2003)	The required build-out rates thus seem to be possible, but it remains to be seen whether the high rate can be maintained over the decades necessary to bring carbon capture up to speed
Availability of CO_2 Compressors	1 compressor per new capture plant would be required	The current size of the CO_2 compressor industry is used as a comparison	While production capacity may initially be limited, the industry would be able to adapt and expand to meet CCS requirements
Creation of CO_2 Transport Networks	Assuming 10% of CO_2 would be transported by ship, the remainder by pipeline. An estimated 4500 - 12,000 km of new CO_2 pipeline/year would be required. CO_2 transport by ship is estimated to increase by 15 - 30 Mtpa	The development of natural gas transportation pipelines is used as a proxy for CO_2 pipeline build-out rates. For shipping estimates, shipping rates of liquefied natural gas (LNG) were used	Natural gas pipeline construction has maintained a build-out rate of 5000 - 9000 km/year since the 1990s, comparable with estimated requirements for CO_2 transport. Shipping of LNG has an average yearly increase of Mtpa CO_2 equivalent. Transport of captured CO_2 is not anticipated to block CCS deployment
Development of CO_2 Geological Storage Sites	Up to 60 storage sites are required to be discovered and developed/year (injecting 5 - 10 Mtpa for 20 years, with final cumulative storage of 100 - 200 Mt). This equates to discovering 3.0 - 5.5 Gt storage resource/year, rising to 6.5 Gt by 2050	Comparison with natural gas discovery rates	Historically, gas fields have been discovered at an average rate of ~6 Gt CO_2 storage/year, suggesting that early-stage storage site discovery rates are feasible, but that exploration efficiency will be required to increase in the future to allow continued CCS development
Deployment of Drilling Rigs/Platforms /Well Pads	1 - 4 wells required per 1 Mtpa of CO_2 injection (to account for failed wells, poor injectivity, monitoring, and production wells). A requirement of between 300 and 1200 new wells per/year after 25 years of growth, ~40 - 100 drilling rigs, and installation of 60 - 120 wellheads or platforms/year	In comparison with historic global drilling rig counts	Historic global drilling rig counts increase and decrease on the order of 300 rigs/year. New rigs can be constructed quickly in response to increased demand, suggesting that the required increase in rigs for storage site development is feasible

Many Oil & Gas companies have made commitments to employ CCS to reduce their net carbon footprint. Shell aims to reduce its net carbon footprint by 35% by 2035 and 65% by 2050, targeting net-zero emissions from product manufacture by 2050. ENI plans to cut overall carbon intensity by 55%, BP aims for a 50% reduction by 2050, and Repsol targets carbon neutrality by 2050.

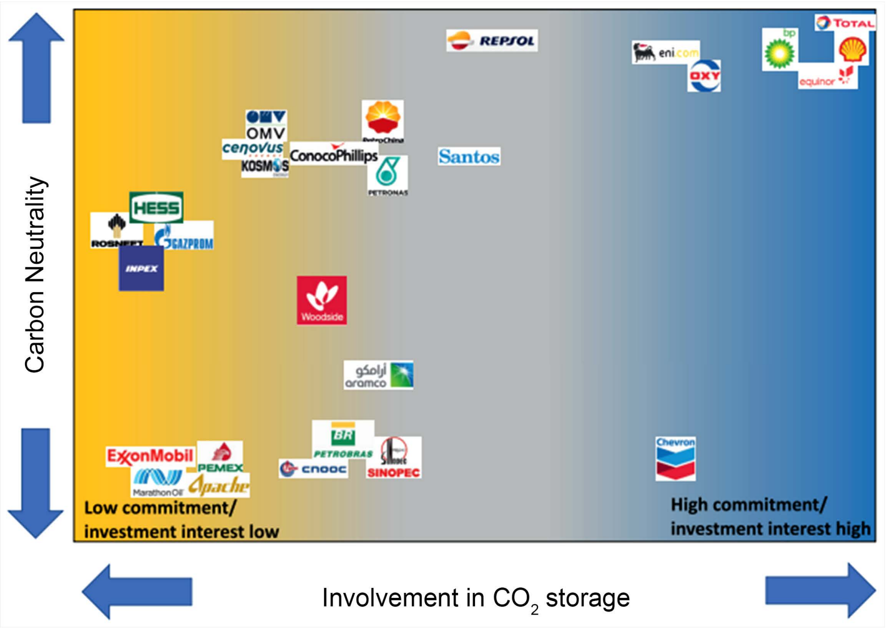

Figure 4. Major oil and gas companies are committed to carbon neutrality (Martin-Roberts et al., 2021).

Companies like Shell and Equinor, with dedicated CO_2 storage operations, contrast with those not committed to net-zero emissions or carbon storage per the Paris Agreement (TPI, 2020). The alignment of major oil and gas firms concerning their carbon neutrality and CO_2 sequestration commitments is depicted in **Figure 4**.

A smaller commitment to CO_2 storage is represented by yellow in the color gradient; a higher commitment is represented by blue, which is already injected in operating facilities; and a gray commitment is mostly related to enhanced oil recovery (EOR) activities. Companies that pledge to cut scopes 1, 2 (operational emissions), and 3 emissions (direct emissions from energy products sold to customers) are eligible for higher levels of carbon neutrality. Based on the CDP research and oil and gas firm league table (Beyond the Cycle report 70), the companies used in this analysis have been updated with the latest company disclosures for this study (Martin-Roberts et al., 2021).

Non-European oil and gas companies, especially in North America and national firms like Saudi Aramco, lag behind European counterparts in net-zero targets. The Transition Pathway Initiative (TPI) assessment (TPI, 2020) noted that none outside Europe aligns with the Paris Agreement, except Petrobras, considering scope 3 emissions. Despite legislative, public, and economic challenges, significant projects like Sleipner, Snøhvit, Shell's Quest, Chevron's Gorgon, and future initiatives (Greensands, Northern Lights, Net Zero Teeside) show investment in CO_2 storage (TPI, 2020). With only 0.12% (**Figure 5**) of annual emissions now being captured globally, the CCS industry is still in its infancy. About 40 commercial facilities use CCS for different purposes, spanning industrial processes, fuel conversion, and power generation (Budinis, Fajardy, & Greenfield, 2023). According to a recent analysis, to achieve net-zero commitments, a minimum of 4.2 gigatons per annum (GTPA) of CO_2 must be captured (Di Fiori, Stackhouse, & Nojek, 2023).

Captured CO_2 is mostly used for EOR due to the resources needed to establish dedicated storage sites, with ~487 million tons used in EOR and ~73 million tons stored in dedicated reservoirs as of 2020. By 2035, dedicated storage is projected to reach over 700 million tons, far below the 6000 - 7000 Mtpa forecast needed by 2050, despite EOR's high storage retention factor (IEA, 2015).

Carbon sequestration tax credits, like the revised 45Q tax credit utilized in the United States, support carbon-capturing initiatives by offering businesses up to $35 per ton of CO_2 used commercially and $50 per ton permanently stored (Price & McLean, 2014). State-run incentives like California's Low Carbon Fuel Standard (LCFS) provide additional credits, encouraging investment and reducing risks for CCS projects, with potential models for other regions (Haszeldine, 2009; Salehabadi et al., 2020).

While US achievements in CCS are notable, Norway has proposed ambitious climate targets to the EU, aiming for a 55% emissions reduction by 2030. Despite ongoing oil and gas exploration, Norway's early strides in CCS are exemplified by the Sleipner and Snøhvit facilities, supported by financial incentives like the 1991 offshore carbon tax (Price & McLean, 2014; Godzimirski, 2022).

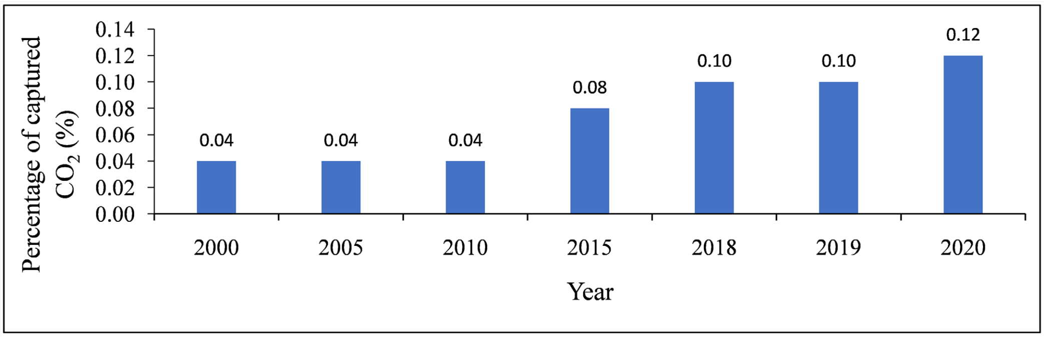

Figure 5. Percentage of CO_2 emissions captured by CCS technology worldwide from 2000 to 2020 (Sources: https://www.statista.com/statistics/1308669/share-of-co2-captured-globally/).

4.3. Challenges to CCS Integration in the O&G Industry

The primary impediment to the widespread adoption of CCS lies in commercial challenges, necessitating substantial investments in capital-intensive components such as capture plants, CO_2 transport pipelines, and geological storage infrastructure (GCCSI, 2020). Evaluating, constructing, and developing these assets incur considerable expenses, and the emissions abatement service provided by CCS often holds minimal or no economic value in many markets.

However, reports show that adding CCS increases costs for power generation processes but decreases them for industries like natural gas. For example, P.C. supercritical costs nearly double from 77 to 133 US$/MWh with CCS, while natural gas costs drop from 3.75 to 0.061 US$/GJ. The cost of avoided CO_2 follows a similar trend (Irlam, 2017). This indicates that although CCS is costly, it is relatively low-cost in the O&G industry.

Additionally, the differences in carbon prices between regions like the US and EU may hinder CCS advancement by causing economic "leakage", where reduced output in one area is offset by increases in another, and it remains uncertain if policies like the EU's Carbon Border Adjustment Mechanism will effectively address this issue (Leal-Arcas, Faktaufon, & Kyprianou, 2022).

Table 2. Areas of challenge and proposed solutions for CCS technologies in the O&G industry.

No.	Areas Involving Challenges	Solution to the Challenges	References
1	Commercial challenges in CCS deployment	Share the cost of CCS between producers and end users	OIES, 2022
2	Capital-intensive assets in CCS	Develop cross-industry hubs that share CCS infrastructure and resources	Fattouh, Heidug, & Zakkour, 2021; Di Fiori, Stackhouse, & Nojek, 2023
3	Emissions abatement value in markets	Implement measures that are cost-effective and can save money	IEA, 2023b
4	Regulations covering the geological storage of CO_2	Establish regulations for the geological storage of CO_2	EU, 2023
5	Long-term liability for stored CO_2	Manage long-term storage liability risks through regulatory, operational, and financial strategies	Havercroft & Trabucchi, 2024
6	Skepticism of CCS	Stay open-minded, and continue to test the capabilities and use cases of CCS technologies	Berra, 2023
7	Cost-effective capture and transport of industrial CO_2	Develop CCS hubs where emission facilities share the same CO_2 transportation and storage or utilization infrastructure	Di Fiori, Stackhouse, & Nojek, 2023
8	Clear access to pore space for CO_2 storage in geologic formations	Establish clear legal frameworks and collaborative agreements to ensure access to suitable pore spaces for CO_2 storage in geologic formations	Birkholzer, Oldenburg, & Zhou, 2015
9	Methodologies demonstrating storage integrity in CCS	Develop standardized monitoring and verification methodologies, implement rigorous reporting protocols, and invest in advanced monitoring technologies	Cherepovitsyn & Ilinova, 2016; Zyrin & Ilinova, 2016
10	Dissemination of best practices in CCS	Establish industry-wide guidelines, knowledge-sharing platforms, and capacity-building programs for best practices dissemination	Viebahn, Vallentin, & Höller, 2015; Larkin, Leiss, & Krewski, 2019

Table 2 presents a general view of the challenges faced in integrating CCS in industrial operations and proposed solutions. Besides the high cost, reports indicate that other obstacles exist. For instance, regulatory uncertainties and long-term liability risks further hinder the attractiveness of CCS projects for investment, exacerbated by notable skepticism from those with a limited understanding of the technology.

4.4. Solutions to the Challenges of Integrating CCS in the O&G Industry

Table 2 shows several challenges in integrating CCS in the oil and gas industry, including high costs, regulatory gaps, and skepticism among those with limited knowledge. Despite these challenges, efforts are underway to find solutions, as demonstrated by the proposed solutions in Table 2. For instance, while the large-scale application of CCS is economically challenging due to the associated high costs, a partnership can be achieved through technical advancement and scientific innovation. Already, cost reductions have been realized at large-scale CCS projects, with the cost of CO_2 capture in the power sector decreasing by 35% from the first to the second large-scale CCS facility (Baylin-Stern & Berghout, 2021). This downward trend in costs is expected to continue as the market expands.

5. Discussion

5.1. Evaluation of Findings

Although the oil and gas (O&G) industry has historically been a major contributor to the world's energy supply, serious environmental concerns have been raised by its high carbon emissions. A turning point was reached in 2015 when the Paris Agreement was signed, which set an ambitious goal of 1.5˚C over preindustrial levels to preserve ecosystem stability and keep global warming well below 2˚C (Guiot & Cramer, 2016). Negative emission technologies (NETs) that can absorb current atmospheric CO_2, such as direct air capture (DAC), bioenergy with CCS (BECCS), and ocean injection, are necessary to achieve these targets.

Notwithstanding the progress made in CCS technology, there are still few thorough analyses of its evolution—particularly in the oil and gas industry. The important role that the oil and gas (O&G) industry played in shaping CCS technology is highlighted in historical literature, along with important knowledge gaps. According to IEA and IPCC theoretical and empirical evaluations, CCS is essential for lowering global emissions; to reach net-zero targets by 2050, it is estimated that roughly 5.6 gigatonnes of CO_2 must be stored annually at a yearly estimated rate of 75 - 150 new global capture facilities (Martin-Roberts et al., 2021).

Since the 1970s, the US has led the way in the development of CCS projects, most notably CO_2-enhanced oil recovery (EOR-CCS) (Beck, 2020). CCS reduces emissions associated with the extraction of fossil fuels, but it does not deal with emissions associated with their consumption. It is becoming more widely accepted that developing CCS technologies, such as BECCS and DACCS, is necessary to reach net-zero emissions targets and convert significant sources of emissions into negative emission centers.

Encouraging net-zero objectives for 2050 have been set by European oil and gas firms, such as Shell and ENI, to drastically lower operational and Scope 3 emissions. Empirical research shows the potential and practical difficulties of carbon capture and storage (CCS). Examples include the integration of biofuels and CCS in the maritime industry, as well as high-throughput synthetic approaches for CO_2

capture materials. These observations are essential for comprehending the application of CCS and resolving technical issues.

Over the past twenty years, CCS technology has advanced significantly, particularly with the adoption of the Paris Agreement. According to the IEA's assessment, it is possible to quickly commission new capture facilities, have CO_2 compressors available, create CO_2 transport networks, find geological storage sites, and deploy drilling rigs—all of which need consistently high build-out rates. With large corporations like Shell, ENI, BP, and Repsol setting considerable reduction objectives by 2050, several oil and gas (O&G) companies have committed to utilizing CCS to minimize their carbon footprints.

Still, in its infancy, the CCS industry only accounts for 0.12% of yearly worldwide emissions. Due to the high costs and resource needs of dedicated storage sites, the majority of captured CO_2 is used for EOR. Financial incentives for CCS are provided by policies such as the US 45Q tax credit and state initiatives such as California's LCFS. These policies can serve as templates for other locations. With its aggressive climate ambitions and early CCS projects like Sleipner and Snøhvit, supplemented by financial incentives like the 1991 offshore carbon tax, Norway is a prime example of proactive CCS deployment. Even with continuous exploration of oil and gas, Norway's dedication to CCS shows that it is possible to reconcile the use of fossil fuels with climate objectives.

Although these difficulties exist, attempts are being made to identify answers. Cost reductions are being driven by scientific and technical breakthroughs, as demonstrated by large-scale CCS projects where CO_2 collection prices in the power sector have dropped by 35%. As the industry expands, it is anticipated that this pattern will persist, highlighting the necessity of alliances and teamwork to overcome the financial and legal obstacles to CCS integration. **Table 2** lists the difficulties and suggestions for incorporating CCS in the oil and gas sector. These include building legal frameworks, controlling long-term storage liabilities, creating cross-industry hubs, implementing cost-effective solutions, sharing costs between manufacturers and end users, and overcoming skepticism through ongoing innovation and testing.

5.2. Reassessment of Research Questions Relative to the Research Findings and Literature

Reassessing Chapter One's research questions against findings and literature confirms that CCS technology is nascent but evolving, crucial for global climate goals, and progressing post-Paris Agreement. The literature supports the assertion that CCS is indispensable in achieving global climate goals (Serin, 2023; UNFCCC, 2023). Moreover, the identified challenges, including high costs and regulatory uncertainties, are consistent with the existing literature (Zapantis, Townsend, & Rassool, 2019; Comello & Brown, 2022). The proposed solutions align with current discourse, emphasizing collaborative approaches, regulatory frameworks, and knowledge dissemination (Viebahn, Vallentin, & Höller, 2015; Larkin, Leiss, & Krewski, 2019). The impact on implementation is multifaceted, requiring coordinated efforts from industry stakeholders.

Furthermore, the feasibility and effectiveness of proposed solutions are contingent on industry-wide collaboration and continuous technological innovation. As the literature demonstrates, ongoing efforts to reduce costs and address regulatory gaps indicate a positive outlook (Baylin-Stern & Berghout, 2021). However, sustained commitment and proactive measures are essential for successful CCS integration.

The analysis reveals advancements and challenges in O&G's CCS adoption, with literature-backed solutions crucial for overcoming obstacles. Continued research, collaboration, and innovation are essential for CCS's potential in reducing emissions. High costs for CCS components and limited commercial value hinder CCS development, exacerbated by regional carbon price variations. The EU's Carbon Border Adjustment Mechanism aims to address this economic "leakage".

6. Conclusion, Recommendations, and Prospects

6.1. Conclusion

This research looks into CCS in the oil and gas industry, evaluating developments, obstacles, and solutions while suggesting sustainable energy shifts. However, through a comprehensive review of the literature, the following conclusions can be drawn relative to the objectives:

With studies such as (IEA, 2016; Budinis, Fajardy, & Greenfield, 2023; Di Fiori, Stackhouse, & Nojek, 2023), the research has provided a detailed examination of the current state of CCS technology in the O&G sector, tracing its evolution from its inception in the mid-20th century to recent advancements. Examples such as the deployment of pilot projects and technological strides have demonstrated the progress made in CCS implementation within the industry.

This research has identified and analyzed primary technological challenges that CCS encounters within the O&G sector, encompassing technical, operational, and regulatory hurdles. Examples include issues related to the cost of capture methods, storage alternatives, and regulatory frameworks impacting CCS deployment (OIES, 2022). Through empirical research, the study has highlighted the complexities of addressing these challenges and the need for innovative solutions to overcome them.

The study has evaluated the feasibility, effectiveness, and potential impact of proposed solutions for mitigating carbon emissions in the O&G sector. Examples such as the integration of biofuels with CCS and incentive policies for CCS projects have been examined to assess their practical implications (Bennett & Heidug, 2014; Mukherjee, Bruijnincx, & Junginger, 2020). These evaluations have underscored the importance of innovative strategies and policy support in accelerating the deployment of CCS technologies and achieving sustainability goals. By providing insights and laying the groundwork for future studies with a sustainability focus, this research advances knowledge of CCS technology in the O&G industry.

6.2. Recommendations for Business Application

Based on what has been discussed above and a review of these sources (Bennett & Heidug, 2014; Cherepovitsyn & Ilinova, 2016; GCCSI, 2020; Comello & Brown, 2022; Havercroft & Trabucchi, 2024; Empson, 2023), the following recommendations for the business application of CCS technology are presented:

Embracing Technological Innovation

O&G businesses should prioritize investing in technology, especially CCS. Adopting new technologies and CCS methods can boost efficiency and sustainability. Resources should be directed towards research and development to improve capture techniques, storage tech, and operations.

Collaboration and Knowledge Sharing

Deploying CCS requires stakeholder cooperation, including governments, academia, and businesses, to share expertise, combine resources, and foster innovation, reducing risks and achieving carbon reduction goals.

Regulatory Engagement and Policy Advocacy

Implementing CCS in the oil and gas industry requires active engagement with regulators and policymakers, advocating for supportive laws, incentives, and regulatory changes. Companies must actively shape policy discussions, offer industry insights, and advocate for regulatory reforms that simplify CCS deployment while ensuring environmental compliance.

Long-Term Strategic Planning

For O&G operations to be sustainable, long-term planning must include CCS technology. Companies should incorporate CCS into risk management, investment planning, and sustainability strategies. Businesses can demonstrate their commitment to the environment, enhance shareholder value, and maintain their competitiveness in the changing energy market by integrating CCS into their fundamental business models.

Capacity Building and Talent Development

Investing in human capital is crucial for supporting CCS initiatives in the O&G sector. Companies should focus on employee training, skill development, and knowledge transfer to build a skilled workforce for CCS projects. They should also promote a culture of innovation, collaboration, and continuous learning to maximize their human capital's potential in driving CCS innovation and sustainability.

Continuous Monitoring and Evaluation

Continuous monitoring, performance evaluation, and adaptive management are essential for CCS project success. Businesses should have robust mechanisms to track performance, assess outcomes, and find improvement areas. By promoting a learning, accountability, and transparency culture, companies can optimize CCS deployment, reduce risks, and boost stakeholder confidence in their sustainability efforts.

6.3. Limitations and Implications for Future Research

6.3.1. Limitations of the Study

While this study provides valuable insights into the current state, challenges, and potential solutions of CCS technology within the O&G sector, it is important to acknowledge several limitations. Firstly, the study primarily focuses on the technological aspects of CCS deployment, potentially overlooking broader socio-economic, political, and cultural factors that may influence its implementation. Secondly, the comprehensiveness of the review and analysis has been constrained due to limited access to proprietary data, confidential industry information, and unpublished research. In addition, the literature predominantly comes from regions with active CCS initiatives, which could lead to missing perspectives from underrepresented areas. Lastly, given the rapidly evolving nature of CCS technology and regulatory frameworks, ongoing updates are necessary, which may render some findings outdated over time.

6.3.2. Implications for Future Research

Future research avenues should be considered to address the limitations identified in this work and advance knowledge in CCS technology within the O&G sector. Future studies should adopt a multidisciplinary approach, integrating insights from various fields to provide a holistic understanding of CCS deployment dynamics. Additionally, conducting longitudinal studies can yield valuable insights into project performance, scalability, and long-term sustainability. Thirdly, emphasizing research efforts in regions with emerging CCS markets can enrich our understanding of regional nuances and global trends in CCS deployment. Moreover, complementing quantitative analyses with qualitative research methods can offer nuanced insights into the human dimensions of CCS implementation. Further, future research should prioritize innovation and technology assessment studies to evaluate the efficacy of emerging CCS technologies. In addition, analyzing the effectiveness of existing policies can inform evidence-based policymaking and regulatory interventions. Lastly, facilitating knowledge transfer and capacity-building initiatives can foster global collaboration, facilitate technology diffusion, and accelerate CCS deployment worldwide.

In conclusion, this study offers valuable insights into CCS technology in the O&G sector but highlights opportunities for future research to overcome limitations and advance sustainable energy goals. The research community can propel meaningful progress in CCS technology and support the transition to a low-carbon future by fostering interdisciplinary collaboration, innovative methodologies, and stakeholder engagement.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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