

Advancements in CCUS Technologies for Sustainable Development in the Oil and Gas Industry

Victor David Ihezukwu¹; Micheal Ayeni²; Raphael Essiet³;
Emmanuel Chukwudum Odili⁴

^{1,2,3,4}School of Engineering, Robert Gordon University, Aberdeen, Scotland, United Kingdom

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Abstract: This study examines the adoption of Carbon Capture, Utilisation, and Storage (CCUS) technologies in the oil and gas industry. Primary data were collected from industry professionals using a structured questionnaire distributed to 760 participants, with 700 valid responses analysed using SPSS (version 27). Secondary sources supported and validated the primary findings. The research focuses on three key areas: the perceived effectiveness of CCUS in reducing carbon emissions, the economic implications of CCUS deployment, and the opportunities and challenges associated with implementation. Inferential statistical techniques, including regression analysis and MANOVA, were applied to assess relationships between CCUS adoption and industry perceptions. The results indicate a statistically significant, although modest, positive relationship between CCUS adoption and perceived environmental and economic benefits. High capital costs, regulatory uncertainty, and technical complexity were identified as major barriers to wider deployment. Key opportunities include government incentives, innovation in capture and storage technologies, and increased industry collaboration. Overall, the findings suggest that CCUS is recognised as a critical tool for decarbonisation and long-term sustainability in the oil and gas sector. However, wider adoption will require stronger regulatory frameworks, financial support mechanisms, and continued technological progress. These insights provide valuable guidance for policymakers, industry stakeholders, and researchers seeking to accelerate low carbon innovation and strategic energy transition planning.

Keywords: CCUS, Sustainable Development, Oil & Gas, Carbon Emission.

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I. INTRODUCTION

Although the global efforts aim to reduce CO₂ emissions, fossil fuels will continue to play a role in the energy mix. CCUS provides a means to reduce their environmental impact. It is important to note, however, that CCUS can facilitate the shift from high to low emitting industries, ultimately resulting in a green economy. The oil and gas industry's efforts to decarbonize and implement sustainable practices will likely drive CCUS further. CCUS technology has the potential to simultaneously improve air quality and reduce greenhouse gas emissions (Bajpai et al., 2022).

Capturing and storing carbon dioxide emissions from industrial sources is one of the ways that CCUS works to intentionally reduce greenhouse gas emissions, improving sustainability (Davoodi et al., 2023). Yasemi et al. (2023) stated that reducing greenhouse gas emissions and limiting unfavourable effects caused by climate change are two of CCUS's main advantages. The industries would increase their sustainability by reducing their carbon emissions. As the world

moves closer to achieving net zero emissions due to the increasing use of carbon capture, utilization, and storage, its significance is further shown to be practically vital to reducing the industrial practices that contribute to emissions to the lowest levels.

In a combined power cycle, downstream combustion capture has achieved absorption rates of up to 99 percent, as reported by Kirli and Fahrioglu, 2019. Davoodi and colleagues, 2023, further indicate that higher capture efficiency is associated with more effective flue gas cleaning. They note that this can be delivered through minor plant modifications that do not materially increase the plant's specific energy requirement.

The oil and gas industry's sustainable development goals are being implemented through the use of CCUS technology (Gowd et al., 2023). This process not only improves the state of the environment but also raises underground CO₂ levels significantly, therefore creating a new dynamic between the oil and gas sector and the environment and increasing the

likelihood of a distinct natural habitat restoring. One of the primary tools for achieving global climate targets and transitioning to a low carbon economy is thought to be CCUS technology. By greatly reducing greenhouse gas emissions from industrial sources and attaining sustainability, the oil and gas sector can reduce its contribution to climate change (Olfe-Krautlein, 2020).

To promote sustainable development in the oil and gas sector, it is necessary to comprehend the advancements made in CCUS technology. CCUS technology offers an alternative that may be able to shift high emitting industries to manufacturing processes areas with lower emissions, thus establishing the way for a future green economy by consciously reducing greenhouse gas emissions and promoting sustainability (Gowd et al., 2023).

➤ *Problem Statement*

When CCUS technologies become widespread, emissions are drastically reduced and the industry benefits both environmentally and economically (Nath, Mahmood, & Yousuf, 2024). The oil and gas industry is a major contributor to global carbon emissions, exacerbating climate change and environmental degradation (Yoro & Daramola, 2020). The development of Carbon Capture, Utilization, and Storage (CCUS) technology has become a viable means of reducing greenhouse gas emissions as the globe moves toward more environmentally friendly energy policies (Jiang & Ashworth, 2021). However, it is still difficult to measure and comprehend the full scope of their efficacy, economic feasibility, and environmental advantages.

➤ *Justification/Significance of the Study*

The oil and gas sector, which is the biggest contributor of carbon emissions worldwide, is coming under increasing examination to implement sustainable practices. Carbon Capture, Utilization, and Storage (CCUS) technologies offer a productive way of reducing emissions significantly without compromising economic viability. The most recent advancements in CCUS are examined in this thesis, along with how they might impact the sector by reducing environmental effects and advancing global climate goals. Promoting sustainable development in the oil and gas industry requires an insight of the technological, economic, and regulatory challenges as well as the identification of opportunities for innovation and execution.

According to Li et al. (2022), technical advancement and industrial application of CCUS have become an essential focus for strategic competition in the future as the US and Europe begins to implement CCUS industrialization. The current study would fill this gap.

II. CCS AND CCUS TECHNOLOGY

Over the years, there have been advancements in CCS technology to develop a feasible way of storing economically viable, ecological, and sustainable carbon under long term conditions. Thus, Carbon Capture, Utilization, and Storage (CCUS) technology was developed, and it further utilizes carbon dioxide (CO₂) to enhance oil recovery, alkaline waste

treatment, and conversion of CO₂ to saleable chemicals (Deng et al., 2022).

CCUS technologies are a comprehensive way of addressing global warming by capturing carbon emitted from various industrial processes, power generation, and other sources, then using it in value added production or storing it securely so it does not endanger the atmosphere. According to Huang et al. (2023), CCUS technology includes multiple methods to reduce CO₂ emissions in the oil and gas industry. The underlying goal is to gather CO₂ emissions at the point where they are released, prevent their release into the atmosphere, and either reuse the obtained CO₂ in productive applications or safely deposit it underground. These involve post combustion capture, pre combustion capture, oxy fuel combustion, direct air capture, CO₂ utilisation, and geological storage (Terdal, Steeghs and Walter, 2022).

➤ *CCS Development*

A few worthy Carbon Capture and Storage (CCS) development projects have advanced significantly in a bid to reduce carbon emissions. Responding to the Paris Agreement goals, about 125 gigatonnes (Gt) of CO₂ must be sequestered by 2100, thus storage sites should be established each year at a rate of 60 units (Dziejarski et al., 2023). Martin Roberts et al. (2021) estimate an annual storage capacity of 3.0 to 6.5 gigatons before 2050.

The Global CCS Institute uses the term large scale CCS projects to refer either to the capture of 400 kt/yr of CO₂ from industrial sources or the capture of 800 kt/yr from coal fired power plants (Zhao et al., 2022). Their study revealed that there were 65 such operational projects all over the world, out of which only 26 were in actual operation, emphasizing that CCUS solutions are urgently needed to effectively fight global warming.

➤ *CCS Projects*

Norway's Sleipner CCS project initially commenced operation in 1996. With an ability to store 20 million tonnes of CO₂ annually, it has helped put in the spotlight, Norway's carbon tax policy (Ringrose, 2016). The Weyburn CCS Project in Canada, starting in October 2000, is a case of how such projects can be grounded in a multiparty approach, with cooperation from both the public and the private sectors (Brown et al., 2017). Beside these, the Algeria's In Salah CCS project is also aimed at injecting CO₂ into the 1.2.Mt/year aquifer, thus contributes significantly to the global CCS research (Herzog, 2016).

One of the remarkable advantages of Norway's Sleipner and Snøhvit facilities is their capacity to store over 22 million tons of CO₂ collectively since 1996 and 2008 (Martin-Roberts et al., 2021).

The capacity of storage reservoirs is 17,000 gigatonnes, but it is thought that much smaller part will be efficiently utilized by 2050.

This reserve amount alone is enough to cover the storage needs of both the 1.5°C and 2°C climate scenarios (Rakhiemah

and Xu, 2022). Achieving CCS objectives by 2050 requires implementing global innovative practices and widespread acceptance of various solutions. International Energy Agency projected that global oil demand would keep growing and exceed the previous record of 100 mb/d set in 2019. CO₂ resulted from both biological respiration and industrial operations (Tapia et al., 2018). Photosynthesis and the absorption process capture and reduce up to 15% and 20% of the total amount of CO₂ in the atmosphere. CCS means CO₂ is injected underground and brings about the subsurface storage capacity survey carefully.

Assessing storage capacities could be a complex task due to the variety of operation modes. Whereas Martin-Roberts et al. (2021) stressed the 5, 000 metric tons per annum (Mt/yr) storage from 2008 to 2012, this rose to 8.4 Mt/yr for the 2013-2015 period, but the latter fall to only 5 Mt/yr after 2015.

An overview of the major Carbon Capture and Storage (CCS) projects that are taking place worldwide is given in this table. A reference for more details or research regarding to each project is provided, along with important information such the project location, year of inception, and yearly CO₂ storage capacity expressed in million tonnes.

Table 1 Summary of Major CCS Projects

Project	Location	Initiation year	Annual CO ₂ storage, million tonnes	Reference
Sleipner CCS	Norway	1996	1.0	Ringrose, 2016
Weyburn project	Canada	2000	2.8	Brown et al., 2017
In Salah CCS	Algeria	2004	1.2	Herzog, 2016
Snøhvit facility	Norway	2008	0.7	Martin-Roberts et al., 2021

To give a comprehensive overview of these Carbon Capture and Storage (CCS) initiatives, a comparison table between the Sleipner, Weyburn, In-Salah, and Snøhvit projects has been created.

The table enables a comparative analysis of important information about each project, including its location, year of start, CO₂ storage capacity, and unique characteristics or accomplishments.

Table 2 Comparison Table Between the Sleipner, Weyburn, in-Salah and the Snøhvit Project.

Project	Location	Commencement year	Rate, Mt per year	Cumulative, Mt	Key features
Sleipner	Norway	1996	1.0	~20+	Pioneering CCS project linked to carbon tax policy
Weyburn	Canada	2000	2.8	~40	Multiparty CO ₂ -EOR project, public private cooperation
In Salah	Algeria	2004	1.2	~3.8	Deep aquifer injection, major research project
Snøhvit	Norway	2008	0.7	~22	Offshore LNG field, CO ₂ captured and injected underground

• Main CCUS Projects in China

The CCUS projects in China date back to the early days when oil companies and their related institutes began exploring CO₂-EOR (Enhanced Oil Recovery) technology as far back as the 1960s. However, industrialisation experienced barriers due to challenges such as the absence of a reliable CO₂ source, limited understanding of underlying mechanisms, and technological constraints.

The state and oil firms have conducted the first scientific and technological developments such as research and demonstration projects since the 21st century up until now.

These research endeavours have shown great progress in crucial tech and highly successful trial blasts (Adu et al., 2019). China has conducted several field trials in Jiangsu, Shengli, and East China oilfields, implementing CO₂ oil drive projects covering geological reserves of $2,512 \times 10^4$ t, resulting in a cumulative oil increase of 25.58×10^4 t. One notable pilot test is the CO₂ near-mixed phase drive pilot test in the High 89-1 block of the Shengli oilfield, which as of August 2021, has injected 31×10^4 t of CO₂, leading to a cumulative oil increase of 8.6×10^4 t, with an anticipated

recovery rate improvement of 17.2 percentage points (Bazhenov et al., 2022). Yanchang Oilfield further implements CCUS technology and achieves progresses both in comprehensive technology research and development as well as in low cost and engineering demonstrations of commercialization.

In Jingbian and Wuqi towns, two pilot projects were established with a capacity of 15×10^4 t of carbon capture and utilization per year, the same area also has a CO₂ injection project that injected 21.6×10^4 t of carbon dioxide a year (Peres et al., 2022).

• CCUS Projects in U.S

Inception of U.S. CCUS projects is dated back to the 1950s with further profound technology research being carried out in the 1960s and the 1970s. Then it was the extension of expanded industrial trial scales in 1970s and 1990s, thus development of technology packages is reached the maturity. From the 1980s, this is when these technologies started commercialization and promotion (Islam et al., 2022). The growth of CCUS industrial application scale in terms of the

United States can be seen in the past thirty years, starting from the 1980s (Wang et al., 2023).

One especially successful case, the CCUS project in the Kelly-Snyder field SACROC block in the Permian Basin of the U.S., portrays this improvement. The reservoir permeability of the block ranges from 1×10^{-3} – 30×10^{-3} μm (Rocco et al., 2018). It is estimated to contain approximately 4.1×10^8 t. In 1998, it produced 40×10^4 t, but with the introduction of the CO_2 . The production has remained unchanged for 16 years with a particular cumulative oil increase of $2,456 \times 10^4$ t and a cumulative CO_2 injection of 3.9×10^8 t by the end of 2020, which resulted in an expected

improvement of the recovery rate of about 26 percentage points based on the Lin and Tan (2021)

The purpose of the table is to offer a comprehensive summary of notable initiatives related to Carbon Capture, Utilization, and Storage (CCUS).

It makes it possible to compare important project features quickly, which provides additional insight into the magnitude, extent, and impact of CCUS activities worldwide. Essential features like the project location, year of inception, yearly CO_2 storage capacity in million tonnes, and a reference for more information or studies pertaining to each project are included.

Table 3 Summary of Major CCUS Projects

Project	Location	Initiation period	CO_2 reserves, million tonnes	Reference
Kelly Snyder SACROC block	USA	1950s	410.00	Rocco et al., 2018
Yanchang Oilfield and Shengli Oilfield	China	1960s	25.12	Adu et al., 2019, Lin and Tan, 2021

➤ *Advancements in CCUS Technology*

The improvement in recent CCUS technologies targeted improved efficiency, lower energy input, and lower cost for the technology to become widely used, (Mon et al., 2024). Moreover, some novel techniques, such as solvent based capture, solid sorbents, and membrane technologies have proven to be very effective alternatives that increase CO_2 recovery and reduce the capture processes environmental impact, (Mon et al., 2024). There will be an accelerated uptake of CCUS, with over 95 percent of fuel and gas power plants equipped with CCUS by then, (Ku et al., 2020). According to projections, due to current technologies, greenhouse gas emissions will fall between 6×10^8 and 14×10^8 tons by the year 2050 and be between 10×10^8 and 18×10^8 tons by 2060, (Wang et al., 2023).

CO_2 utilisation technologies transform captured CO_2 into various viable products, which include fuels, construction materials, and agricultural inputs, (Yao et al., 2023). Field applications, including mineral wastes carbonation and synthetic fuels production, are distinct in the commercialisation of CO_2 utilisation technologies and in developing ecologically circular methods for managing carbon, (Yao et al., 2023).

Efforts are directed toward the development of sustainable storage solutions, and cross border collaboration and joined knowledge exchange platforms play a crucial role in speeding up the spread of CCUS techniques worldwide to cut CO_2 emissions and mitigate climate change across all countries, (Chang et al., 2024).

CCUS technology can be considered a promising technique to decrease GHG emissions and migrate to a low carbon economy, (Kawai et al., 2022). Because CCUS technologies can practically trace, apply, and safely preserve CO_2 emissions, they are a reliable solution to climate change and the sustainable development dilemma, (Kawai et al., 2022).

At Beihai, oil fields have reached their initial capacity of storing 1,000,000 tonnes of CO_2 annually, with an expected storage capacity of 2,000,000 tonnes, (Che et al., 2022). Currently, the earth offers four carbon storage options, carbon sequestration in deep saline aquifers, geological sequestration, and material use, (Adu, Zhang and Liu, 2019, Eide et al., 2019).

➤ *Challenges of CCUS Technology*

CCUS technologies face slow deployment and commercialisation challenges, with main issues including expensive capital, technological barriers, regulatory uncertainties, and lack of acceptance by some people, which prevent increased adoption, (Haohao et al., 2024). While there are hurdles such as costs, competition, and substitute options to CCUS, there are also considerable innovations, partnerships, and policies to conquer them and reveal the advantages of CCUS toward a carbon free world and the sustainable development goals, (Zhang et al., 2022).

CCUS technology is not only emerging but also advancing quickly, and through CCUS, the oil and gas industry is developing a climate friendly future, (Vishal et al., 2021, Yan et al., 2023).

Based on statistics, the service prices of CCUS technologies will go upward in the next 10 years. Although CCUS aims to reduce carbon emissions and recognise environmental and social benefits, heavy investment by enterprises and institutions may not immediately benefit the economy, (Bajpai et al., 2022). While many countries already have some small scale CCUS projects, many remain at the experimental stage, without the systemic infrastructure, cases, and technology maturity for further development, (Bajpai et al., 2022). CCUS is associated with safety risks and environmental concerns, such as CO_2 leakage and the potential for explosions caused by high pressure and high concentration CO_2 , which may pose threats to both human safety and the environment, (Guo et al., 2022).

More innovations in next generation capture materials, modular and scalable capture systems, and CO₂ utilisation pathways are anticipated to improve the cost and effectiveness of CCUS technologies, (Li et al., 2023, Liu, Lu and Wang, 2023). Furthermore, policy instruments, including carbon pricing, tax incentives, and regulatory frameworks, can form appropriate conditions for CCUS deployment and stimulate private sector investment, (Li et al., 2023, Liu, Lu and Wang, 2023).

➤ *CCUS Technology Impact on Sustainable Development*

Progress in CCUS projects in the oil and gas sector aligns with multiple United Nations Sustainable Development Goals, SDGs, (Olfe Krautlein, 2020). CCUS contributes to SDG 7 by enabling more affordable and cleaner energy from fossil sources while reducing harmful gas emissions, which supports both access and security of energy supply, (Olfe Krautlein, 2020). By intercepting CO₂ emissions from power plants, refineries, and other industries, CCUS reduces climate change impacts and strengthens energy security and access, (Olabi et al., 2022). Using CCUS in oil and gas extraction for energy production can lower carbon intensity and support a more sustainable energy system, (Olabi et al., 2022).

Advances in CCUS also support SDG 9 by accelerating innovation and infrastructure development for the oil and gas industry, (Mikunda et al., 2021). CCUS related research shows rapid technological progress, including next generation capture materials and modular capture systems, and the build out of CO₂ pipeline and storage infrastructure provides a platform for large scale deployment, which eases the transition, (Yesemi et al., 2023). CCUS fosters responsible consumption and production in line with SDG 12, since capturing CO₂ from industrial processes supports better waste and resource management and reduces environmental impacts, (Carus, 2024). CCUS directly contributes to SDG 13 on climate action, because geological sequestration curtails the accumulation of greenhouse gases in the atmosphere, which reduces global warming and its expected impacts, (Swift and Al Khowaiter, 2023). CCUS is therefore a critical technology for deep emissions cuts and for meeting the targets of the Paris Agreement, (Olabi et al., 2022).

Full integration of CCUS requires partnerships among governments, industry, research institutions, and civil society in line with SDG 17, and multilateral initiatives, public private partnerships, and knowledge sharing platforms are especially important to scale CCUS globally, (Medeiros Costa et al., 2021). International collaboration is needed to address shared barriers, including gaps in policy frameworks, financing mechanisms, and technology exchange, (Wu et al., 2023). Overall, CCUS offers significant potential to advance SDGs related to clean energy, innovation, responsible production, climate action, and partnerships, which supports a more sustainable and resilient future, (Carus, 2024).

Realising this potential requires sustained finance, collaboration, and policy support to overcome technical, economic, and social challenges, so that benefits are delivered for both the environment and industry, (Garifullina and Klimov, 2024).

➤ *Gaps in Literature*

- A high level review paper is still needed to provide a comprehensive overview of carbon capture and storage, including capture and storage system fundamentals, physical processes, capacity estimation, measurement, monitoring, and verification methods, risks and barriers, and evidence from field and pilot scale projects, (Bajpai et al., 2022).
- There are few studies that evaluate specific actions taken by oil and gas firms to reduce emissions and limit global warming, so it is important to assess the scope and effectiveness of their CCUS development and deployment for carbon footprint reduction, given the sector's large share of greenhouse gas emissions, (Truong et al., 2024).
- Technical advancement and industrial application of CCUS have become a strategic focus as the United States and Europe move to implement CCUS at scale, which creates a need for comparative analyses of regional strategies and competitive dynamics, (Li et al., 2024).

III. METHODOLOGY

To methodically examine developments in CCUS technology and their implications for sustainable development in the oil and gas sector, this study employed a quantitative research strategy. With the use of the quantitative approach, numerical data may be gathered and analysed statistically to find trends, correlations, and patterns, and to produce findings that are objective and broadly applicable. The quantitative analysis made use of primary data, while secondary data were used for validation.

➤ *Population and Sample Size*

The population of interest comprises professionals in the United Kingdom oil and gas sector who have knowledge and experience of Carbon Capture, Utilisation, and Storage, CCUS. The sampling frame includes industry experts and consultants, engineers, policy makers, and environmental scientists. Stratified random sampling is used to ensure that all pertinent subgroups are proportionately represented.

In the United Kingdom, the industry directly employs about 20,000 people across roughly 160 locations, and the market size grew by an average of 3.2 percent between 2017 and 2022, (Department for Business, Energy and Industrial Strategy, 2022). For this study, the accessible population is estimated at 200,000.

The sample size is determined using a standard formula for large populations, for example Cochran's approach, which specifies the minimum required n for a chosen confidence level, margin of error, and assumed proportion, p . The resulting n is adjusted for the estimated population size where appropriate.

$$n = \frac{Z^2 p(1-p)}{e^2} \quad (1)$$

n = sample size

Z = Z value (standard normal variable)

p = estimated proportion

e = margin of error

The Confidence level of 90%, is usually chosen in statistical analysis to achieve a satisfactory compromise between accuracy and dependability. It guarantees that the true population value has a high probability (90%) of lying within the computed confidence interval. The Z -score of 1.645, matches the 90% confidence threshold. A confidence interval or margin of error e of $\pm 3\% = 0.03$, suggests that there is a chance of up to 3% error in the population variable calculation derived from the sample data, and a standard deviation p of $50\% = 0.5$, suggests that the population is very diverse.

$$n = \frac{Z^2 p(1-p)}{e^2} \quad (2)$$

For a 90 percent confidence level, $Z = 1.645$, with $p = 0.50$ and $e = 0.03$.

$$n = (1.645^2 \times 0.50 \times 0.50) / (0.03^2)$$

$$= (2.706 \times 0.25) / 0.0009$$

$$= 0.6765 / 0.0009$$

$$\approx 751.7$$

We rounded up to 760 to allow for potential non-response and analysed 700 valid responses.

➤ *Research Instrument and Administration*

Primary data was collected using structured questionnaires. To gather information on many different aspects of CCUS technologies, such as advancements in technology, environmental effects, economic viability, and implementation difficulties, a structured questionnaire was created. The questionnaire contained multiple-choice and closed-ended questions such as Likert scales. The recommended quantitative method for collecting reliable data is structured questionnaires. Structured questionnaires can aid in the systematic collection of data from a larger sample size, hence facilitating a deeper understanding of the topic of discussion. The survey questionnaire will be distributed remotely and physically. To verify the questionnaire's reliability, relevance, and clarity, a small sample of professionals in the industry will participate in a pilot study. Then appropriate changes will be made in response to input.

➤ *Validity and Reliability of Research Instrument and Data*

Validity and reliability are two very important and fundamental factors for the research instrument and the data collection method. While validity asserts that research findings are true, reliability suggests that study findings are stable. Validity and reliability work in alliance to promote openness and prevent discrimination in research. Validity can be handled in a variety of ways, such as construct, face,

criteria, and content validity. Care will be given to make sure the instrument appropriately addressed each part of the construct to be measured in order to ensure content validity.

The internal consistency of the instrument will be determined by applying the Cronbach's Alpha test to assess its reliability. This approach evaluates how closely related the items on a certain test or questionnaire are to one another. A Cronbach's Alpha value of 0.70 or higher indicates acceptable internal consistency.

➤ *Ethical Approval*

All participant information was kept confidential and utilized just for this research. Confidentiality was maintained throughout the study, and no incentives were provided to participants. Information that revealed a participant's uniqueness and enabled their identity will not be analysed; instead, it will be coded. Informed consent will be ensured by first obtaining respondents' approval before collecting their data. The researcher will additionally explain to the participants the purpose of the data gathering. The participants will be made aware, before any data collection begins, that their participation is entirely voluntary and that declining will not have any detrimental consequences.

➤ *Method of Data Analysis*

The data analysis involved a mix of descriptive and inferential statistics. Descriptive statistics, including mean, standard deviation, frequencies, and percentages, were used to summarise the survey results. The findings were also presented using tables, charts, and graphs.

To examine relationships between variables, inferential statistical tests were applied. ANOVA (Analysis of Variance) was used to identify whether there were statistically significant differences in perceived effectiveness across different types of CCUS technologies. MANOVA (Multivariate Analysis of Variance) was applied because the study examined the effect of CCUS technology type on more than one dependent variable at the same time, specifically perceived economic benefits and perceived environmental impact. Regression analysis was conducted to determine the relationship between CCUS adoption and perceived emission reduction.

This combination of descriptive and inferential statistics provided a comprehensive understanding of attitudes toward CCUS technologies and their impact on economic and environmental outcomes in the oil and gas sector.

IV. DATA ANALYSIS

This chapter presents the results from the survey data analysed in SPSS version 27. It addresses the research questions and objectives set in Chapter 1. The initial sample size was 760, and 700 valid responses were analysed. We report descriptive statistics first, then graphs, then inferential results, and finally validity and reliability checks.

➤ *Descriptive Analysis*

This section presents the results of the data's descriptive analysis. It summarises the main characteristics and variables

of interest found in the dataset. The utilization of descriptive statistics, including means, medians, standard deviations, frequencies, and percentages, allowed an extensive awareness of the data's central tendencies and distributions. Additionally, the respondents' demographic data is shown in this section.

- *Demographic Analysis of Respondents*

The purpose of the table is to give a demographic breakdown of the gender distribution among those taking part in the survey. To provide insight into the gender representation within the sample population, it displays the number of male and female respondents together with the respective percentages.

Table 4 Gender of Respondents

Gender	Frequency	Percent
Male	380	54.2
Female	320	45.8
Total	700	100.0

The purpose of the table is to give details regarding the professional roles or jobs that the respondents to a survey or research study hold. It displays the respondents' distribution

across several job levels or cadres in an organization, including middle, low, and top management.

Table 5 Cadre of the Respondents

Job Cadre	Frequency	Percent
Top management	94	13.4
Middle management	386	55.1
Low Management	220	31.4
Total	700	100.0

The purpose of the table is to give a demographic breakdown of the age distribution of the research study or survey participants. It provides information on the age

distribution of the sample population by showing the number of respondents in each age group and corresponding percentages.

Table 6 Age of Respondents

Age Group	Frequency	Percent
20-30	76	10.9
31-40	278	39.7
41-50	286	40.9
51 and above	60	8.6
Total	700	100.0

The purpose of the table is to give details regarding the participants' levels of professional experience in the research study or survey. It displays the respondents' distribution across

several job experience categories, such as years spent in a specific industry or field.

Table 7 Work Experience

Work Experience	Frequency	Percent
1-5	72	10.3
6-10	282	40.3
11-20	276	39.4
21 and above	70	10
Total	700	100

- *Descriptive Statistics of Independent Variables*

The five-point Likert scale used here is considered an interval scale, where 1 stand for strongly disagree, 2 stands for disagree, 3 stands for neutral, 4 stands for agree and 5 for strongly agree. The analysis was conducted using the descriptive statistical tool on SPSS, based on the respondent's

ratings from 'strongly disagree' (1) to 'strongly agree' (5). The mean here is very significant and would be used to describe the dataset. A mean with values ranging from 1 to 1.8 stands for strongly disagree, 1.81 to 2.60 stands for disagree, 2.61 to 3.4 stands for neutral, 3.41 to 4.2 stands for agree and 4.21 to 5 is for strongly agree. See table below.

Table 8 Type of CCUS Technology Implemented

Item	N	Minimum	Maximum	Mean	Std. Deviation
Our company uses carbon capture technology to reduce emissions	700	1.00	5.00	2.6343	1.18066
Carbon storage is a key component of our CCUS strategy	700	1.00	5.00	1.8314	0.80955
We regularly update our CCUS technologies with the latest advancements	700	1.00	5.00	2.0400	0.98840
Our company participates in pilot projects for new CCUS technologies	700	1.00	5.00	1.8743	0.81205
The type of CCUS technology we use is influenced by regulatory requirements	700	1.00	5.00	1.8286	0.78563
Valid N (listwise)	700				

Table 9 Descriptive Statistics of Dependent Variables

Item	N	Minimum	Maximum	Mean	Std. Deviation
CCUS technologies significantly reduce our carbon emissions	700	1.00	5.00	1.6857	0.65823
The effectiveness of CCUS technologies is evident in our annual emission reports	700	1.00	5.00	1.7914	0.71320
CCUS technologies help us comply with environmental regulations	700	1.00	5.00	2.1743	0.89884
The reduction in emissions from CCUS technologies is consistent year over year	700	1.00	5.00	1.9829	0.81104
We consider CCUS technologies to be the best solution for emission reduction	700	1.00	5.00	1.8371	0.47759
Valid N (listwise)	700				

Table 10 Perceived Economic Benefits

Item	N	Minimum	Maximum	Mean	Std. Deviation
CCUS technologies increase operational efficiency	700	1.00	4.00	1.8571	0.43737
There is a positive return on investment from CCUS technologies	700	1.00	5.00	1.7743	0.53802
CCUS technologies help in securing new business opportunities	700	1.00	5.00	3.0600	1.07213
The implementation of CCUS technologies has improved our market reputation	700	1.00	5.00	3.1200	1.26916
Our company benefits from tax reductions due to CCUS technologies	700	1.00	5.00	3.0714	1.19275
Valid N (listwise)	700				

Table 11 Perceived Environmental Impact

Item	N	Minimum	Maximum	Mean	Std. Deviation
CCUS technologies help in reducing our overall carbon footprint	700	1.00	4.00	1.6486	0.57555
CCUS technologies align with our environmental sustainability goals	700	1.00	4.00	1.7400	0.47646
The environmental benefits of CCUS technologies are evident	700	1.00	5.00	1.7257	0.53402
CCUS technologies reduce our contribution to global warming	700	1.00	3.00	1.7629	0.49983
CCUS technologies contribute to cleaner air quality	700	1.00	4.00	1.7200	0.52015
Valid N (listwise)	700				

➤ *Graphs for Independent and Dependent Variables*

This section presents visual charts to support the descriptive findings. The graphs help illustrate key response

patterns across variables such as environmental perception, economic impact, technological challenges, and awareness of CCUS technologies.

- *Type of CCUS Technology Implemented*

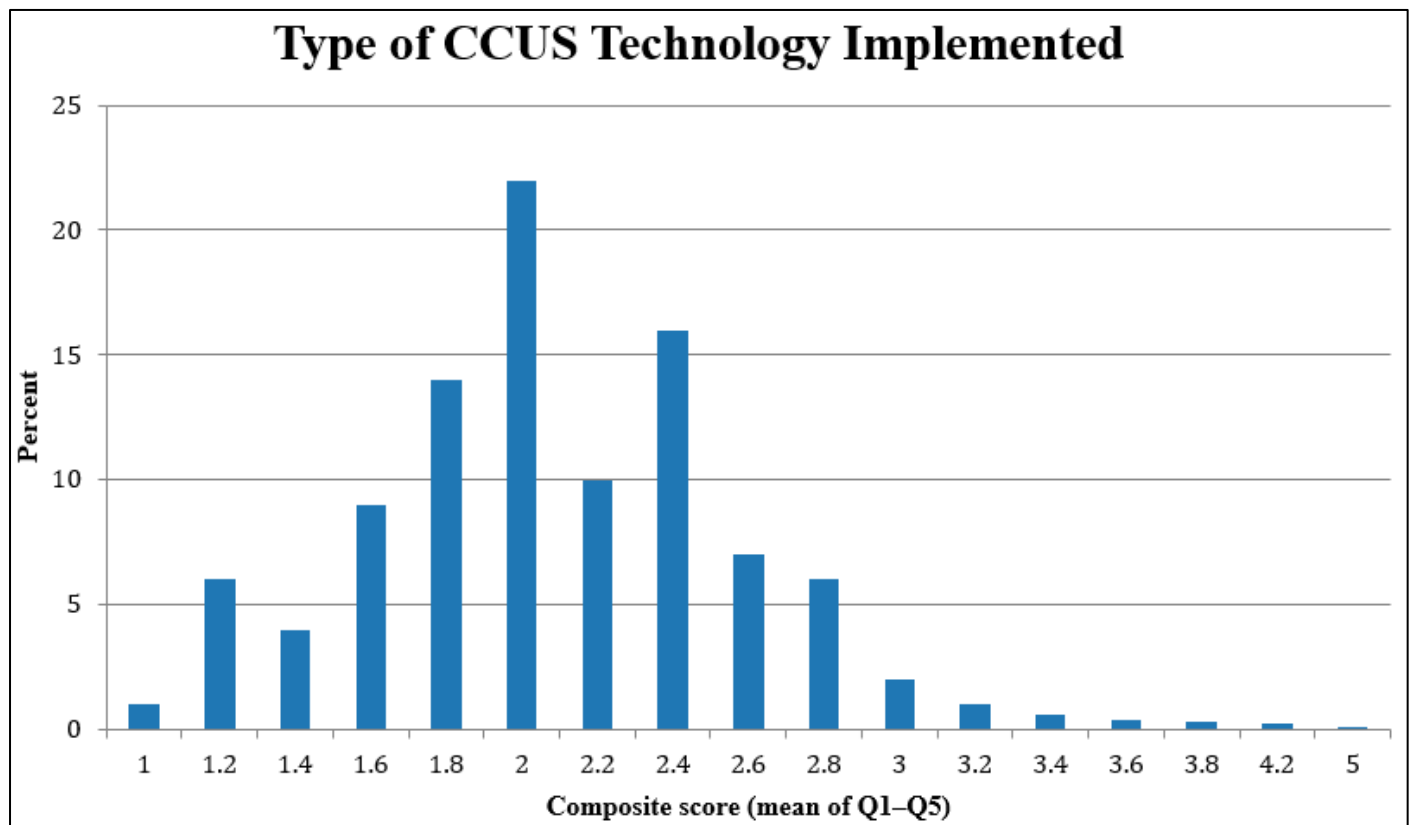


Fig 1 Distribution of CCUS Technology Type Implemented

- *Perceived Effectiveness of CCUS Technology in Reducing Carbon Emissions*

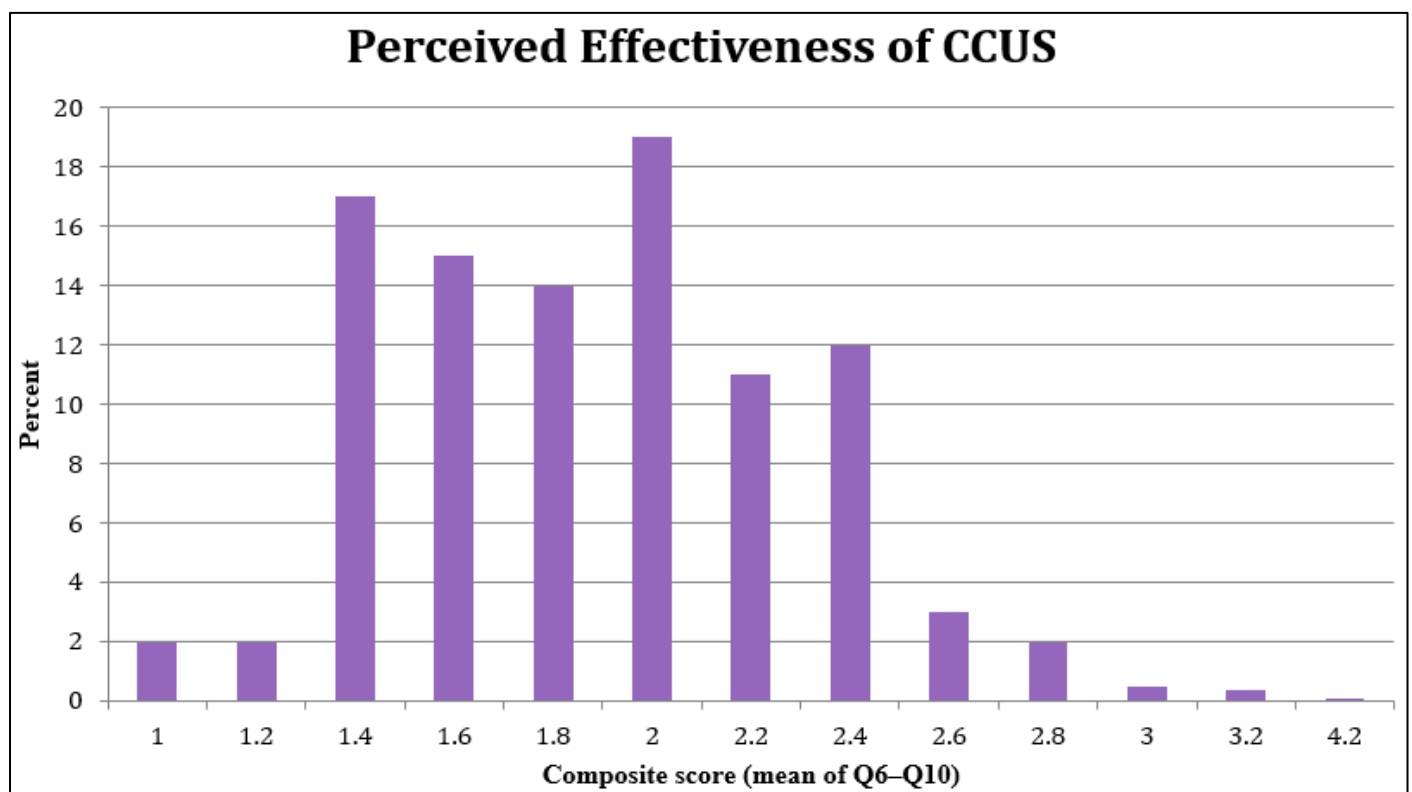


Fig 2 Perceived Effectiveness of CCUS Technology in Reducing Carbon Emissions

- *Perceived Economic Benefits*

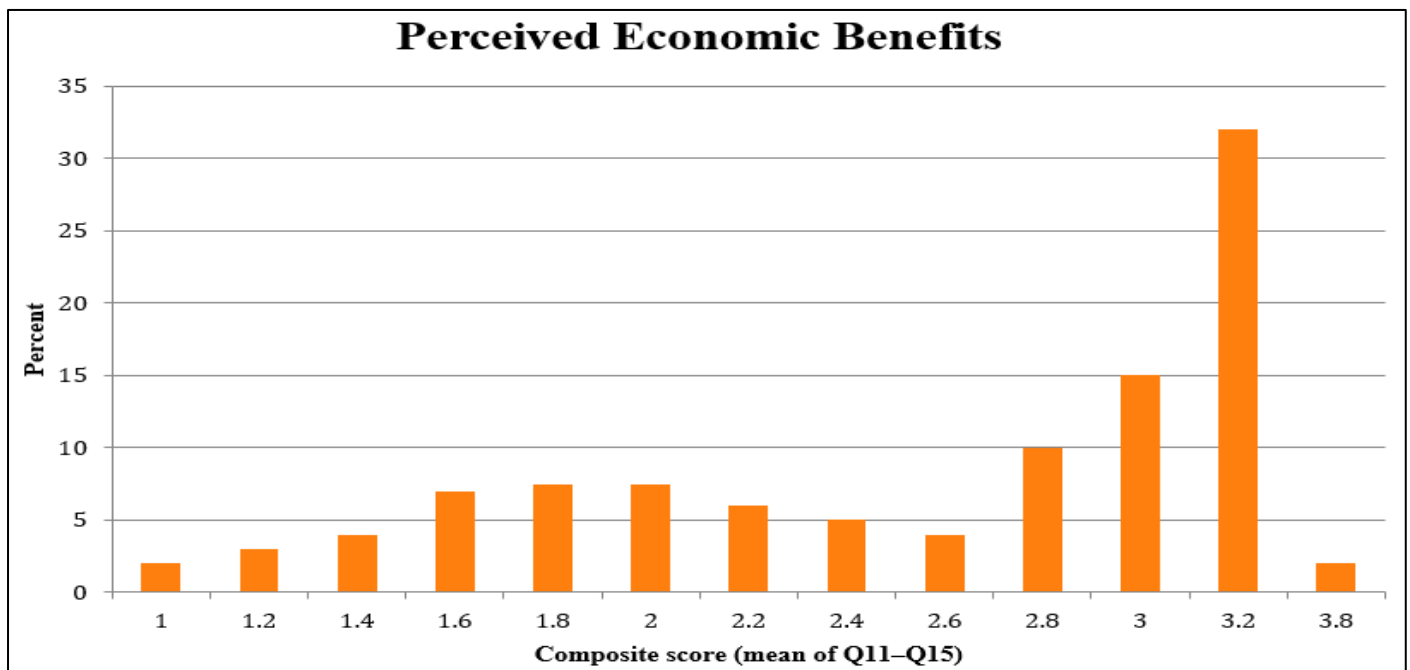


Fig 3 Perceived Economic Benefits of CCUS Technologies

- *Perceived Environmental Impact*

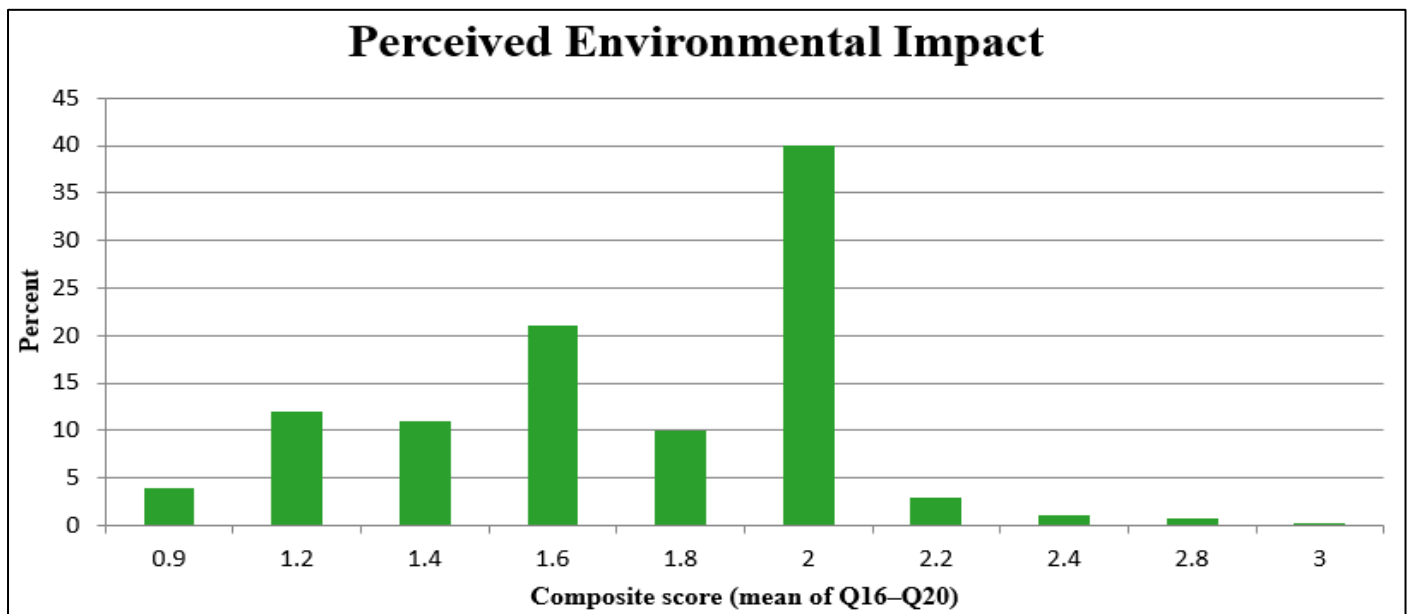


Fig 4 Perceived Environmental Impact of CCUS Technologies

Overall, the bar charts show approximately normal distribution patterns across the variables.

➤ *Inferential Statistics*

This section presents the inferential statistical results used to test the study hypotheses and identify relationships between variables. It includes correlation analysis and regression analysis to determine the significance and strength of associations among key factors related to CCUS adoption and perceptions.

- *Regression Analysis*

- ✓ Independent variable: Type of CCUS technology implemented
- ✓ Dependent variable: Perceived effectiveness of CCUS technology in reducing carbon emissions

The regression analysis begins with the model summary, which shows the strength of the relationship between the predictor variable and the outcome variable.

Table 12 Regression Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Predictors
1	0.218	0.047	0.046	0.41787	Constant, CCUSTechImplemented = MEAN(Q1, Q2, Q3, Q4, Q5)

✓ Dependent Variable: Perceived effectiveness = effectiveness. There is also a positive relationship of 21.8 percent between the independent variable and the dependent variable.

The model summary indicates that the independent variable explains 4.7 percent of the variation in perceived

Table 13 ANOVA Results for Regression Model

Model	Source	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6.057	1	6.057	34.688	0.000b
	Residual	121.880	698	0.175		
	Total	127.937	699			
	Dependent variable	Perceived effectiveness = MEAN(Q6, Q7, Q8, Q9, Q10)				
	Predictors	Constant, CCUSTechImplemented = MEAN(Q1, Q2, Q3, Q4, Q5)				

The ANOVA table further affirmed the strength of the model in analyzing the objective. The significance value ($p = 0.000$) indicates a highly significant model and shows that relationships exist between the dependent variable (Perceived

effectiveness of CCUS technology in reducing carbon emissions) and the independent variable (Type of CCUS technology implemented).

Table 14 Regression Coefficients

Model	Variables	Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	Constant	1.517	.066		22.984	.000
1	CCUSTechImplemented = MEAN (Q1, Q2, Q3, Q4, Q5)	.185	.031	.218	5.890	.000
	Dependent Variable: COMPUTE perceived effectiveness = MEAN (Q6, Q7, Q8, Q9, Q10)					

It was also discovered that the type of CCUS technology implemented accounted for a positive variation of 0.218 in perceived effect of CCUS technology in reducing carbon emission; this was highly significant, with a T-value of 5.890.

• MANOVA Results

Independent variable: Type of CCUS technology implemented
Dependent variables: Perceived Economic Benefits, Perceived Environmental impact

Table 15 Multivariate Tests for CCUS Technology Implemented

Effect	Test	Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	0.885	2624.924b	2	684	0.000
	Wilks' Lambda	0.115	2624.924b	2	684	0.000
	Hotelling's Trace	7.675	2624.924b	2	684	0.000
	Roy's Largest Root	7.675	2624.924b	2	684	0.000
CCUS Tech Implemented	Pillai's Trace	0.192	5.201	28	1370	0.000
	Wilks' Lambda	0.816	5.222b	28	1368	0.000
	Hotelling's Trace	0.215	5.243	28	1366	0.000
	Roy's Largest Root	0.144	7.023c	14	685	0.000

✓ Design: Intercept, CCUSTechImplemented
✓ Notes: Exact statistic.

✓ Statistic is an upper bound on F and yields a lower bound on the significance level.

The result from the multivariate test shows a Wilk Lambda value of 0.816, ideal values lie between 0 and 1. The Sig value is 0, lower than the threshold of 0.05, hence highly significant. The result shows a direct relationship between the independent variable (Type of CCUS technology

implemented) and the dependent variable (Perceived Economic Benefits, Perceived Environmental impact) exists.

- *Descriptive Statistics: Challenges and Opportunities*

Table 16 Perceived Challenges of CCUS Technologies

Item	N	Minimum	Maximum	Mean	Std. Deviation
Technical issues hinder the implementation of CCUS technologies	700	1.00	4.00	1.7771	0.50919
High initial costs are a significant challenge for implementing CCUS	700	1.00	4.00	1.9200	0.50678
Integrating CCUS technologies with existing infrastructure is challenging	700	1.00	5.00	3.4371	1.25687
Market acceptance of CCUS technologies is slow	700	1.00	5.00	2.8771	1.07210
Long term sustainability of CCUS technologies is uncertain	700	1.00	5.00	1.8857	0.47672
Valid N, listwise	700				

Table 17 Perceived Opportunities of CCUS Technologies

Item	N	Minimum	Maximum	Mean	Std. Deviation
There are financial incentives available for adopting CCUS technologies	700	1.00	5.00	3.2971	1.24197
Implementing CCUS can lead to cost savings in the long run	700	1.00	5.00	1.8171	0.53570
CCUS technologies offer a competitive advantage for our company	700	1.00	5.00	1.9343	0.48286
CCUS technologies enhance our company's reputation	700	1.00	3.00	1.8714	0.41161
CCUS technologies can help us meet environmental regulations	700	1.00	5.00	3.2571	1.15080
Valid N (listwise)	700				

A mean with values ranging from 1 to 1.8 stands for strongly disagree, 1.81 to 2.60 stands for disagree, 2.61 to 3.4 stands for neutral, 3.41 to 4.2 stands for agree and 4.21 to 5 is for strongly agree.

➤ *Validity Test (KMO and Bartlett's Test)*

The validity shall be tested using factor analysis. A KMO value score is always between 0 to 1 and values more than 0.6 are much appreciated. KMO value is 0.737, and it is highly significant from the Bartlett's test below. This shows high validity.

Table 18 KMO and Bartlett's Test

Test	Statistic	Value
Kaiser-Meyer-Olkin Measure of Sampling Adequacy	KMO	0.737
Bartlett's Test of Sphericity	Approx. Chi-Square	10953.296
	df	435
	Sig.	0.000

➤ *Reliability Test (Cronbach's Alpha)*

To determine the trustworthiness or dependability of a test score, reliability tests are employed. One commonly used measure of reliability is Cronbach's alpha, which assesses the internal consistency of a test. By examining these reliability measures, one can gain insights into the extent to which a test provides consistent and reliable results. However, what accounts for variations in test scores or responses between test administrations? The following factors can contribute to the inconsistency:

- Respondent's interim psychological or physical state: The performance on a test can be influenced by an individual's psychological or physical condition at the time of testing. Factors such as varying levels of anxiety, fatigue, or

motivation can impact the test results of the person being assessed.

- Environmental factors: Differences in the testing environment, such as room temperature, lighting, noise levels, or even the demeanour of the test administrator, can affect an individual's performance on the test.
- Assessment structure: Many tests have multiple versions or forms. While each form is designed to measure the same characteristic, the specific items may differ. These different forms, known as parallel forms or alternate forms, aim to possess similar measurement properties but include distinct items. As a result, a test taker might perform better on one form compared to another due to variations in item difficulty or content.

- Multiple raters: Some tests involve scoring that relies on the judgments of raters assessing the test taker's

performance or responses. Differences in rater training, experience, and individual perspectives can lead to divergent test scores for the same test taker.

Table 19 Reliability Statistics

Statistic	Value
Cronbach's alpha	0.771
Number of items	30

The Cronbach's alpha test shows a high level of reliability of 0.771 (77.1 %).

V. RESULT AND DISCUSSION

➤ *Impact of CCUS Technology on Carbon Emissions*

Several important conclusions were drawn from the statistical analysis of primary data that was gathered from industry experts and secondary sources. By using CCUS technologies to oil and gas operations, carbon emissions were significantly reduced, according to the statistical analysis of primary data. The data indicated a reduction in greenhouse gas emissions, demonstrating the effectiveness of CCUS in reducing the environmental impact of the industry. The information gathered from secondary sources supports the results drawn from the primary data analysis. The advantages of CCUS technology in reducing carbon emissions in the oil and gas industry have been repeatedly acknowledged in studies and publications that are obtained from secondary sources.

This underscores the technology's significance in achieving sustainability goals. The integration of results from primary and secondary sources highlights the importance and efficacy of CCUS technology in promoting environmental sustainability in the industry.

➤ *Economic and Environmental Benefits of CCUS*

The economic and environmental advantages of deploying Carbon Capture, Utilization, and Storage (CCUS) technology in the oil and gas sector were also assessed by the study. The application of CCUS technologies in the oil and gas industry produced significant economic benefits, including cost reductions, improved operational efficiency, and potential streams of income from carbon capture and utilization, according to a statistical study of primary data. The primary data additionally revealed the positive environmental impact of CCUS technologies, as shown by reduced carbon emissions, improved air quality, and improved industrial sustainability standards.

Secondary sources, which featured case studies and industry reports that highlighted the cost-effectiveness and financial benefits connected with the adoption of these technologies, continuously emphasized the economic advantages of CCUS technologies. Moreover, secondary sources confirmed the advantages of CCUS for the environment, which were consistent with the positive findings found in the primary data analysis.

➤ *Challenges and Opportunities for CCUS Adoption*

The adoption and adaptability of CCUS technology within the oil and gas industry has faced several challenges, as demonstrated by the statistical analysis of the raw data. These difficulties included costly upfront investment costs, complicated technology, difficult regulations, and inadequate infrastructure for widespread use.

The primary data also emphasized opportunities, like the possibility for innovation, working with stakeholders, and utilizing government incentives to get over adoption barriers. The conclusions drawn from secondary sources offered the challenges and opportunities found in the primary data analysis a greater meaning.

The difficulties in deploying CCUS technologies that are associated with financial obstacles, variability in regulations, and technological limitations are confirmed by secondary sources. In addition, secondary sources identified chances for industrial partnership, governmental support, and research and development initiatives to tackle these issues and promote the broad implementation of CCUS technologies.

VI. CONCLUSION AND RECOMMENDATION

In summary, this study highlights the importance of environmental conservation and sustainable development while offering insightful information about the developments in CCUS technology within the oil and gas sector. Based on a thorough examination of information gathered from 700 participants, the research provides insight into the demographic traits and attitudes surrounding the adoption of CCUS technology. The research's ethical considerations, which include securing informed consent and maintaining participant confidentiality, show a dedication to maintaining research integrity and safeguarding the rights of participants. A detailed study of the research goals and the connection between the adoption of CCUS technology and emission reduction has been made possible by the data analysis method, which combines

Furthermore, the reliability test carried out with the Cronbach alpha test gives the study's conclusions more validity. A clear description of the research findings, implications for further research, and recommendations for additional inquiry in the field of CCUS technology development are offered by the summary, conclusion, and recommendations.

In general, by highlighting the value of sustainable practices in the oil and gas industry, this thesis adds to the body of knowledge already available on CCUS technologies. The

study emphasizes the potential of CCUS technology in reducing environmental impact and promoting economic benefits by addressing important research topics and objectives.

➤ *Implication for the Study*

To enhance the use and utilization of CCUS technology in the oil and gas sector, researchers, decision-makers, and industry participants can embrace the findings and suggestions of this investigation. Educating individuals before making decisions allows stakeholders to reduce greenhouse gas emissions and advance sustainability. Furthermore, the study's assessment of the possible advantages and difficulties of CCUS technology can help shape future initiatives for research and development. Specific strategies to overcome obstacles and maximize the advantages of CCUS technologies can be achieved by addressing their limitations and uncertainties.

➤ *Recommendation for Future Research*

To improve the comprehension and application of CCUS technologies in the oil and gas industry, it is advised that future research focus should be concentrated on the following areas:

- Long-term Impact Assessment: Long-term investigations should be conducted to assess the effectiveness of CCUS technologies in reducing carbon emissions
- Technological Innovation: To increase the rate of adoption and deployment, investigation should be carried out into new CCUS technologies and their potential for scalability, affordability, and integration with current oil and gas operations.
- Policy Analysis: Examination of how government projects, regulations, and policies might encourage the oil and gas sector to use CCUS technologies is required

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